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MODIFIED RADIOACTIVE FILTER TRANSPORTATION PACKAGE: ACCIDENTAL IMPACT SIMULATION FOR 9 M DROP ORIENTATIONS

OHRD Report No. 90-1-K

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ABSTRACT

Packages used in the road transportation of low level radioactive wastes must demonstrate the ability to withstand severe impacts such as those prescribed by the AECB regulations. One such package is the Radioactive Filter Transportation Package (RFTP). Structural assessments of the most recent design subject to postulated accidental impact scenarios involving two 9 m drop orientations were carried out using 1/4 scale analytical models. Particular emphasis was given to the overpack lid to body bolted connection which has undergone modification.

The results indicate that structural integrity of the RFTP will be maintained following impact. The new design modifications at the overpack lid to body connection have improved the ability of the bolted connection to absorb energy during the top down, c of g over edge and near side, impact orientations. This is necessary to ensure that no gross separation of the overpack lid from the body occurs.

The report presents the analytical methods used, the development and description of the simulation models, result of the simulation, and conclusions.

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EXECUTIVE SUMMARY

MODIFIED RADIOACTIVE FILTER TRANSPORTATION PACKAGE: ACCIDENTAL IMPACT SIMULATION FOR 9 M DROP ORIENTATIONS

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Packages used for the road transportation of low level radioactive wastes must demonstrate the ability to withstand severe impacts such as those prescribed by AECB regulations. Currently, the Nuclear Engineering Department (NED) at Ontario Hydro is in the process of designing, building and licensing the Radioactive Filter Transportation Package (RFTP).

Previous analyses performed on the RFTP for 9m bottom down center of gravity over edge drops show that the structural integrity of the primary containment boundary and the overall integrity of the overpack body is not compromised. However, the postulated fire accident which occurs following the impact makes it imperative that the overpack lid does not separate to such an extent that a direct thermal path is provided to the internal seal area. Therefore, additional analyses and tests for 9m top down drops addressed the extent of damage to the overpack lid-to-body interface as well as to the overpack structure.

As a result of all of the analyses and tests, the RFTP was modified to maintain a secure connection between the overpack lid and body. The new design utilizes long ductile bolts capable of absorbing more impact energy than the previously used short bolts. Also, in the new design the inner containment vessel is no longer integral with the overpack body.

The modifications to the RFTP are significant enough to warrant further analysis. In view of results from the earlier analyses, the two most severe impact scenarios are the top down centre of gravity over edge drop and the near side drop. Only these two drop orientations are considered.

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The analysis is performed using the Ontario Hydro version of the nonlinear transient dynamic finite element program, DYNA3D. Symmetry permits the use of a half model which is analyzed in 1/4 scale to enable direcc comparison of results with 1/4 scale physical tests.

The results indicate that for both drop orientations, the maximum effective plastic strains are below allowable limits and thus the structural integrity of the primary containment boundary is maintained. The overpack lid connecting bolts deform to allow about one inch (in full scale) of separation between the overpack lid and body for the centre of gravity over edge drop. The bolts are not strained enough to cause failure so that no gross separation of the overpack lid is expected. In the side drop orientation, the rim of the overpack lid extending over the overpack body inhibits any shearing action that could be transferred to the bolts. Consequently, most of the bolts are only slightly deformed for this drop.

In conclusion, the analytical results demonstrate that, under the prescribed impact conditions, the modified RFTP overpack effectively isolates the floating inner containment vessel and primary containment boundary from excessive damage. Even though the analysis indicates that the overpack lid to body connection is secure, an increased margin of safety could be achieved by:

i) increasing the number and/or size of overpack lid bolts to minimize separation;

ii) increasing the clearance between the overpack lid bolts and bolt holes to preclude premature shearing of the bolts;

iii) modifying the overpack lid bolt shanks so that the root diameter of the thread is greater than the shank to reduce the possibility of localized failure near the threads.

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MODIFIED RADIOACTIVE FILTER TRANSPORTATION PACKAGE:
ACCIDENTAL IMPACT SIMULATION FOR 9M DROP ORIENTATIONS

1.0 INTRODUCTION

Packages used for transporting low level radioactive waste by road must demonstrate the ability to withstand severe accidental impacts such as those prescribed by the Atomic Energy Control Board (AECB) regulations/1/. Currently, the Nuclear Engineering Department (NED) is in the process of designing, building and licensing the Radioactive Filter Transportation Package (RFTP). The work described herein is supplemental to the analysis carried out in /2/ and /3/ where an alternative RFTP design was evaluated for 9m drops in several orientations including centre of gravity over edge drops (top and bottom down) and a near side drop. The results of the analytical assessments in /2/ and /3/ indicate that the structural integrity of the primary containment boundary and the overall overpack body is maintained during the impact scenario considered. In addition, the results of the analytical work in /2/ are in excellent agreement with results of a comparable experiment.

The overpack, considered to be a sacrificial energy absorbing medium, is expected to experience significant deformation. It has been demonstrated, from both analysis /2,3/ and physical tests /4/, that adequate protection for the containment boundary is provided. However, the postulated fire accident which occurs following an impact makes it imperative that the overpack lid does not separate to such an extent that a direct thermal path is provided to the internal seal area. In an effort to improve the design of the RFTP and increase the factor of safety, a modified RFTP design has been proposed by NED.

Thus, at the request of NED /5/ a detailed analytical investigation of the 1/4 scale modified RFTP has been carried out for the following orientations:

i) 9m top down centre of gravity over edge drop
ii) 9m near side drop on lid

The 1/4 scale package, shown in Figure 1.1, comprises a payload, foam dunnage, inner containment vessel, and a polyurethane foam-filled overpack. The overpack is a sandwich construction of foam walls between 304L stainless steel

liners. The primary containment boundary consists of a separate inner vessel made of 304L stainless steel. The design analyzed is based on the design drawings in Appendix A1.

2.0 METHODS OF ANALYSIS

2.1 Finite Element Analysis Program

The non-linear transient dynamic analysis of impacting structures involves both non-linear geometric and material behaviour affecting wave propagation in two and three-dimensional continua. A two-material structure such as the RFTP, where steel and polyurethane foam interface, further complicates the problem. Due to the inherent complexity of the problem, the finite element method is applied using the latest Ontario Hydro version of the computer code DYNA3D /6/.

The DYNA3D code is an explicit three-dimensional finite element computer program for analyzing the large deformation dynamic response of inelastic solids. A contact algorithm permits gaps and sliding along zone boundaries and material interfaces. These interfaces can be tied to admit mesh refinement without the need for transition regions. Spatial discretization is achieved by the use of eight-noded isoparametric solid elements, four-noded thin shell elements (Belytschko-Lin-Tsay formulation /6/) and two-noded linear isoparametric beam elements. A number of material models and equations of state are available to cover a broad range of material behaviour including elastic-plastic, soil, crushable foam, and explosive-structure interaction. The equations of motion are numerically integrated using the central difference operator. This scheme is explicit and, as a result, is conditionally stable with respect to time step size. A continuous monitor of the time step is made throughout the solution to ensure that it is below a critical time step which is required to maintain operator stability.

Comparisons of analyses with experiments given in references /2/, /6/, and /7/ show excellent agreement between analytical predictions and experimental results. This clearly demonstrates the applicability of the DYNA3D computer code to the class of problems considered herein. Further details of the code along with verification cases, a users manual and theoretical documentation are given in /6,8/.

Initially, a data file defining the analytical model geometry, material, integration parameters and output controls is created. Then, the program is executed and database files for data processing are generated. Computer programs for processing the data in terms of structural deformed plots at selected times (PLOTD), displacement/velocity time history plots and stress/strain measures for comparison with acceptance criteria (POSTD) have been developed to interface with the DYNA3D computer code. Details of the pre- and post-processors are given in reference /6/. To increase efficiency and to enable results at intermediate simulation times to be sampled for trends, a restart capability is available. A simplified flow chart of the computational sequence is given in figure 2.1.1.

A monitoring routine has been written for VAX computers which permits DYNA3D batch runs to be interrogated for current levels of X, Y and Z direction momentum, kinetic energy, strain energy, current solution time and time step. This allows the status and convergence of the solution to be periodically inspected.

2.2 Material Models

For the severe impact scenario addressed in this analysis, the solid material models used must be capable of providing an adequate representation of the moderately large strain regime. This entails a non-linear description of the material behaviour in the post-yield region in terms of:

(a) A yield criterion to determine the threshold at which plastic flow begins;

(b) A flow rule to relate plastic strain increments with total strain and stress increments;

(c) A hardening rule to specify the modification of the yield condition during plastic flow; and

(d) In the case of the polyurethane foam, an equation-of-state for pressure versus volumetric strain with compaction.

The input specification of the material constitutive relations are given in terms of logarithmic strain versus stress. Further information regarding various stress and strain measures for path dependent material properties used in large deformation analyses is given in references /6,8-11/.

The structure of the RFTP consists of four basic material types:

(a) 304L stainless steel
(b) Nitronic steel bolts
(c) 19 lb/ft^3 polyurethane foam
(d) 17.5 lb/ft^3 polyurethane foam

The parameters used to idealize each of these materials are developed and given in the following sections.

2.2.1 304L Stainless Steel and Nitronic Steel Models

The ductile behaviour of 304L stainless steel is characterized by the curves shown in figure 2.2.1, depending on the stress-strain measure used. These curves are representative of the typical behaviour of a ductile material loaded first in uniaxial tension followed by uniaxial compression. The straight line approximations serve to idealize this behaviour. A von Mises yield criterion is adopted with an isotropic hardening rule. Referring to figure 2.2.1, the straight line approximation used in the computer models is characterized by an elastic modulus E, a yield stress of σ_y a strain hardening modulus E_t, and a hardening parameter $\beta = 1$ for isotropic hardening.

The material properties for 304L stainless steel and Nitronic steel used in the models are listed below in Table 2.1.

TABLE 2.1

	304L SS	*Nitronic*
Density, ρ	.29 lbf/in^3	.29 lbf/in^3
Modulus of Elasticity, E	28 x 10^6 psi	28 x 10^6 psi
Poisson's Ratio, μ	.28	.28
Yield Stress, σ_y	44,300 psi	50,000 psi
Bulk Modulus, K	21.2 x 10^6 psi	21.2 x 10^6 psi
Shear Modulus, G	10.9 x 10^6 psi	10.9 x 10^6 psi
Strain Hardening Modulus, E_t	2.2 x 10^5 psi (true stress-strain)	0 psi (perfectly plastic)

Measured response as well as the idealized stress-strain curve used to represent the 304L SS are shown in figure 2.2.2. The data was obtained from reference /10/. The nitronic steel is assumed to be perfectly elastic-plastic which is a reasonable assumption considering the stress-strain curve for nitronic steel given in Appendix A2.

This isotropic elastoplastic material model is simulated using material type 3 in DYNA3D/6/.

2.2.2 Polyurethane Foam Model

Polyurethane foams exhibit a pressure dependent behaviour as voids crush and compact under applied loading and pressure. The model used is based on /7,12/, which describe a simple but useful model for soils and crushable foams whose material properties are not easily characterized. An elementary isotropic plasticity theory is utilized in which a pressure dependent flow rule governs the deviatoric behaviour, and the yield function is defined as:

$$\phi_s = J_2 - (a_o + a_1\sigma_p + a_2\sigma_p^2)$$

where J_2 is the second invariant of the deviatoric stress tensor, σ_p is the hydrostatic pressure and a_o, a_1, and a_2 are user supplied constants. The pressure versus yield curve can then be described as shown in figure 2.2.3. The development of the expressions for a_o, a_1 and a_2 is given in Appendix A3.

The value of effective yield stress is determined using $(a_o + a_1\sigma_p + a_2\sigma_p^2)$ based on hydrostatic pressure, σ_p, and if exceeded, remains at this value for subsequent pressures.

The pressure versus volumetric strain behaviour is shown in figure 2.2.4 for various strain measures. Elastic unloading is assumed to a tensile cutoff pressure using an unloading bulk modulus as shown in figure 2.2.4. If failure under hydrostatic tension occurs, pressure is left at the cutoff value and the deviatoric stress components are zeroed. Note that pressure is positive in compression.

The data used to determine the constants for the 19 lb/ft^3 polyurethane foam material model is based on the experimental results obtained in reference /13/. The samples used were taken from the actual foam material to be used in the RFTP. The data required for input in DYNA3D consists of a volumetric strain versus pressure curve for an equation of state with compaction in (figure 2.2.4), constants a_o, a_1 and a_2 for the pressure dependent yield surface (figure 2.2.3), an unloading bulk modulus K_o, shear modulus G, and pressure cutoff σ_{po}. A parabolic pressure dependent flow rule as described in Appendix A3 is assumed (i.e. $a_2 = 0$). The properties for the 19 lb/ft^3 polyurethane foam used in the analysis are:

G - shear modulus = 9369.44 psi

σ_{po} - cutoff pressure = -223.84 psi (negative in tension)

K_o - $1. \times 10^6$ psi (during unloading)

Using this data and the equations in Appendix A3:

a_o - 22317.4

a_1 - 99.7

Thus, the equivalent uniaxial (effective) yield stress σ_y is given in terms of hydrostatic pressure as:

$$\sigma_y^2 = 3\,[22317.4 + 99.7\,\sigma_p]$$

The curve of pressure versus yield used in the analysis is given in figure 2.2.5.

In reference /13/, a compressive engineering volumetric strain versus pressure curve was obtained as shown in figure 2.2.6. This curve is digitized and converted to true volumetric strain versus pressure for DYNA3D as indicated in figure 2.2.4. In the absence of data for the 17.5 lf/ft^3 foam, the volumetric strain versus pressure curve is scaled according to density so that the pressure required to compact the lighter foam is reduced. Aside from this property and density itself, all other material properties for the 17.5 lb/ft^3 foam are assumed to be the same as for the 19 lb/ft^3 foam.

In order to provide assurance that the numerical model described above accurately predicts the response of the polyurethane foam, experimental benchmarks were conducted in references /2,6,7/. Excellent correlation with experiment was observed. Further details are given in Appendix A3.

The crushable foam material model is simulated using material type 10 with equation of state type 8 in DYNA3D /6/.

2.3 Finite Element Model

2.3.1 Subassemblies of Model

The overall model for the drop simulation consists of the package assembly and the target. Due to the highly localized nature of this accident scenario, mesh refinement was confined to the vicinity of initial impact. The overall drop configuration is shown in figure 2.3.1 which shows the arrangement with the centre of gravity over the impact point.

Symmetry about a vertical plane permits the use of a half model as shown in figure 2.3.2. The package assembly is modelled using four basic components which are divided into subcomponents with weight breakdown (1/4 scale) as follows:

```
                                -----  beam elements (Nitronic bolts, .76 lbf)
                               |
Overpack Lid ------------------|-----  shell elements (304L SS, 27.2 lbf)
                               |
                                -----  solid elements (foam, 8.08 lbf)


                                  ---  shell elements (304L SS, 62.7 lbf)
                    --- Top ---|
Overpack Body ----|             ---  solid elelents (foam, 18.46 lbf)
                  |
                   --- Bottom ----  solid elements (rigid, 26.04 lbf)


                                  ---  shell elements (304L SS, 12.9 lbf)
                  --- Vessel--|
Inner Package ---|              ---  solid elements (304L SS bolt block,
                 |                                   10.7 lbf)
                 |
                 |--- Dunnage ----  solid elements (foam, 16.65 lbf)
                 |
                  --- Payload ----  solid elements (rigid, 109.35 lbf)


Target --------------------------  solid elements (rigid)
```

The four basic components correspond to physical components that are connected through contacting surfaces. Therefore, the various finite element idealizations of the RFTP parts are assembled via interface (contact) surfaces. The only exception to this is the beam elements modelling the overpack lid connecting bolts. These beam elements are directly connected to nodes both on the lid and on the overpack body.

2.3.2 Mesh Generation

The node coordinates are defined in a local right-handed coordinate system with the local x' and y' axes in the base plane and the z' axis vertical on the container centreline (figure 2.3.1). The plane of the symmetry is defined by the local x' and z' axes. In the local coordinate system, the package is up side down so that the bottom of the model extends upward to a total height of 27.0 inches. The model is made up of 4892 nodes, 3418 solid elements, 1695 shell elements, and 36 beam elements in total.

The top surface of the overpack lid, generated as a two-dimensional grid consisting of 284 nodes and 258 elements, is shown in figures 2.3.3 and 2.3.4. The mesh provides the refinement needed in the vicinity of the initial impact point (node 37) while maintaining the total model at a reasonable size. Hence, the elements become progressively larger with increasing distance in the negative-x and positive-y directions. The y=0 boundary is the plane of symmetry. The lid of the RFTP model is generated by replicating layers from this base mesh (figure 2.3.5).

The overpack body is made up of two pieces. The bottom part is made of a very coarse but uniform mesh of 8 noded solid elements. These elements simply represent the mass of the overpack body distant from the impact zone and thus they are rigid elements assigned an equivalent density that corresponds to the mass of the region. The remaining top portion of the overpack body was generated from a two-dimensional grid (figures 2.3.6 and 2.3.7) consisting of 161 nodes and 132 elements. Four noded shell elements are used to model the stainless steel walls of the overpack body. Also, two rows of very thick shells represent the bolt block for the overpack lid connection. The space between the shells is filled with eight noded solid elements for the polyurethane foam. Figure 2.3.8 shows the substructuring of the overpack body while figure 2.3.9 shows the complete overpack body assembly. Note that the bottom and top portions are connected by a tied interface condition.

The containment vessel residing inside the overpack assembly is modelled with four noded shell elements for the steel walls and 8 noded solid elements for the bolt block. The remainder of the model consists of the payload and the foam dunnage. These components, made up of 8-noded solid elements, are intended to simulate the mass and inertial effects of the remaining package. The discretization of the inner package is based on the two dimensional grid shown in figures 2.3.10 and 2.3.11. Figure 2.3.12 is an exploded view of the solid element substructures while figure 2.3.13 shows the complete assemblies of shell and solid elements. The complete inner package model is shown in figure 2.3.14. The containment vessel, payload, and foam dunnage share common nodes where they join so tied interface constraints are not required.

The impact target shown in figure 2.3.15 is modelled using eight noded solid elements as a four inch thick layer of rigid material with the bottom surface fully supported. As with the package, the target is a half model with symmetry about the y=0 plane.

2.3.3 Interface Surfaces

The four basic model components are connected via interface surfaces which are referred to as master and slave surfaces. In all, six sets of master/slave surfaces are defined. Figure 2.3.16 shows all of the interface surfaces superimposed on the package and target. Pictorial views of the master and slave surfaces are given in figures 2.3.17 and 2.3.18 respectively. A clearance exists between the overpack components and the inner containment vessel. Thus, the inner vessel is free to float inside the overpack until it bears against part of the overpack via an interface surface. The overpack lid contacts the overpack body through several interface surfaces that allow for contact between the inside of the rim of the lid as well contact between the top surface of the overpack body and the underside of the lid. The overpack lid is kept from separating from the overpack body by bolts modelled as beam elements. These are shown in figure 2.3.19 where a portion of the lid shells along with some of the bolt block shells can be seen.

The sliding interface surfaces used in the analysis are capable of modelling contact forces between contacting bodies, sliding and separation of previously contacting bodies. The only interface condition not of this type is master/slave set 4 which is a tied interface condition. This condition is used to join unevenly discretized meshes.

The loading on the model is obtained by the interaction of the package on the target through a sliding interface condition. The nodes in the package are given an initial velocity equivalent to the terminal impact velocity of a 9m drop. The target remains fixed in position and as the package impacts the target, contact forces are generated to resist the downward motion of the package. The initial velocity applied to the nodes defining the package is determined from the following relation from rigid body mechanics:

$$V_o = [2gh]^{1/2}$$

where: V_o = initial velocity at impact (in/sec)
h = drop height (in)
g = gravitational constant (386.4 in/sec/sec)

For h = 354.33 in. (9 m) V_o = 523.3 in/sec

2.3.4 Geometric Transformation

The mesh described in section 2.3.2 was generated in the most convenient system, that is, about the centre of revolution. Once the total model was generated in its local coordinate system, it remained to transform the model into the drop configuration. In the case of the centre of gravity over edge drop, this is done by estimating the angle θ required to ensure that the centre of gravity is directly over the initial point of impact (figure 2.3.1). Then the following transformation:

$$(X) = [T]\,(X')$$

$$\begin{Bmatrix} X \\ Y \\ Z \end{Bmatrix} = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{Bmatrix} X' \\ Y' \\ Z' \end{Bmatrix}$$

is applied to the nodal coordinates where [X] is a vector of rotated coordinates representing the drop configuration and [X'] is the vector of coordinates in the original local coordinate system. The analysis is carried out in the rotated system as shown in figures 2.3.1 and 2.3.2.

2.4 General Assumptions

The following assumptions were made to facilitate the analysis:

(a) In the 9 m drop the RFTP is assumed to impact an unyielding surface. This is a conservative assumption since in reality no surface is unyielding. Even small plastic distortions of the target surface result in reduced strains /14/.

(b) To account for the weight of the bottom portion of the overpack body and the payload, an equivalent density, /3/, is calculated for elements representing these parts of the model. These elements are remote from the area of impact and thus are considered to act as rigid bodies. Due to the highly localized nature of the impact, this assumption does not affect the final response /2,7/. The area in close proximity, however, is modelled accurately in order to capture as closely as possible the impact response.

(c) The long bolts connecting the overpack lid to the body are modelled with beam elements. However, since there is no interface condition for beam elements in DYNA3D, these bolts behave as if they have unlimited clearance and their response is dictated only by the motion of the end points connected to the overpack lid and bolt block.

(d) Due to the symmetry of this drop scenario, only one half of the package is modelled.

(e) 1/4 scale dimensions for the RFTP are considered to permit direct comparison with scale model drop test results.

(f) Drop angle is estimated to be 40 degrees for the centre of gravity over edge drop based on /3/.

(g) Strain rate sensitivity is ignored for the 304L SS and Nitronic steel material. For the range of impact velocities considered in this analysis, this assumption is justified /10/.

(h) The analysis is discontinued when the initial impact energy and momentum is dissipated.

(i) Acceptance criteria based on reference /15/ and listed in Appendix 4 are used to assess the integrity of the RFTP.

2.5 Scaling Laws

In order to compare the results of analysis and experiment with the full scale RFTP, the following relationships between scale model (m) and full scale prototype (p) are used:

Displacement	Y_m	=	Y_p/n
Velocity	V_m	=	V_p
Acceleration	A_m	=	nA_p
Stress	S_m	=	S_p
Force	F_m	=	F_p/n^2
Energy	E_m	=	E_p/n^3
Mass	M_m	=	M_p/n^3
Time	T_m	=	T_p/n

where n = 4 for 1/4 scale model.

These relations must be applied when comparing the analysis and scale model experimental results to the full scale RFTP.

3.0 ANALYTICAL RESULTS

3.1 9m Top Down Centre of Gravity Over Edge Drop

The 9m centre of gravity over edge drop simulation was run to 8 ms. The localized nature of this problem is readily observed in figures 3.1.1 through 3.1.10 showing the progression of deformation from the initial to final configuration.

Visible in the final configuration (figures 3.1.9 and 3.1.10) is the limited separation of the overpack lid from the overpack body on the side of the package opposite the impact point. This separation is due to the action of the inner containment vessel bearing on the overpack lid and thus straining the overpack lid connecting bolts. The maximum strain in the bolts is 5.2% which allows for separation of about one inch of the overpack lid in the full scale RFTP. The deformed geometry of the bolts in figure 3.1.11 shows that the two bolts closest to the point of impact have buckled but the remaining bolts appear to be straight. In fact, the last seven bolts are all in tension. The strains of all nine bolts are listed in Table 3.1.1.

With the modified RFTP design, the inner containment vessel is not integral with the overpack. Consequently, more load is imparted to the overpack lid bolted connection during the transient. Further evidence of the force exerted

on the overpack lid by the inner containment vessel appears in figure 3.1.12 where the extent of indentation of the underside of the overpack lid can be seen.

TABLE 3.1.1

Bolt	Strain
1	-- (buckled)
2	-- (buckled)
3	.0092
4	.0203
5	.0288
6	.0360
7	.0453
8	.0517
9	.0483

Figures 3.1.13 and 3.1.14 are separate views of the deformed geometry of the overpack lid and overpack body respectively. A more detailed account of the progression of the deformation in the overpack lid is obtained from figures 3.1.15 and 3.1.16 showing the spread of contact of the overpack lid edge with the target and the contact of the rim of the lid with the overpack bolt block.

In figure 3.1.17a, the peak impact force for the half model is seen to be 78730 lbs. in the drop direction. For the 1/4 scale package, this corresponds to a maximum deceleration $\ddot{z}_m$ of 269 g. Thus, the maximum deceleration of the full scale RFTP is 67.2 g. From figure 3.1.17b, the time to dissipate the total drop energy is seen to be about 7 ms. In figures 3.1.18 and 3.1.19, the time histories of displacement and velocity of node 4539 which is near the centre of gravity are given respectively. A maximum displacement of 2.33 inches at the payload is observed. Figures 3.1.20 and 3.1.21 show the displacements of the inner containment vessel and the outside corner of the RFTP opposite the impact point.

In order to provide some insight into the integrity of the RFTP under this impact condition, various elements of the structure were examined in detail. Of interest is the area in close proximity to the initial location of impact. The time histories of hydrostatic stress for a selection of foam elements are plotted in figures 3.1.22 and 3.1.23. Although the foam has been crushed considerably, it has not been completely compacted even in the worst elements. Figures 3.1.24 and 3.1.25 are colour fringe plots depicting the hydrostatic stress in the overpack lid and body foam elements at the time when maximum impact force occurs (6 ms). The foam elements between the steel plate in the dunnage and the inner containment vessel lid undergo compressive strain of less than 1%.

Effective plastic strain in the shell elements of the overpack lid, overpack body, and inner containment vessel are shown in figures 3.1.26 to 3.1.31 and the hydrostatic stress plots in figures 3.1.32 and 3.1.33 indicate whether the strains are compressive or tensile. The strains are within acceptable limits except where the rim of the overpack lid contacts the very rigid bolt block of the overpack body. In this region, very high strains result when high impact forces are exerted on the bolt block by the edge of the lid plate. This local effect will not have a deleterious effect on the structural integrity of the container. Effective plastic strains in the inner containment vessel shell elements are below 0.3%, and the maximum hydrostatic stress is 28400 psi. (tension).

3.2 9M Top Down Near Side Drop (85°)

The finite element model analyzed in Section 3.1 is also used for the near side drop analysis. However, in this case the model is rotated through an angle of 85° from the horizontal. The initial configuration of the near side drop model is shown in figures 3.2.1 and 3.2.2. followed by the deformed plots in figures 3.2.3 to 3.2.9 showing the progression of deformation over the course of the impact analysis.

The final deformed configuration (figures 3.2.8 and 3.2.9) shows the extent of deformation in the vicinity of initial impact, while some bulging of the dunnage below the payload is just noticeable. Separate deformed plots of the overpack lid and overpack body in figures 3.2.10 and 3.2.11 show more detail of the localized deformation while figures 3.2.12 and 3.2.13 show the time history of the spread of contact of nodes near the impact point. Not visible in the deformed plots of figures 3.2.10 and 3.2.11 are the extensions of the nine bolts connecting the overpack lid to the body. The highest plastic strain of 3.3% (tensile) occurs in the bolt closest to the impact point. The remaining bolts all have strains of less than 1.2% (tensile) as listed in Table 3.2.1.

TABLE 3.2.1

Bolt	Strain
1	.0329
2	.0058
3	.0102
4	.0113
5	.0094
6	.0065
7	.0066
8	.0033
9	.0005

The package to target impact force time history in figure 3.2.14a shows a very prominent peak at about 4 ms. This is a byproduct of the approximate rigid body model of the bottom portion of the overpack body contacting the target

after the initial impact and is thus not a meaningful result. In view of the kinetic energy time history in figure 3.2.14b, more than 60% of the kinetic energy is dissipated before the secondary impact and the curve is leveling out, indicating that the initial impact in fact reaches completion. Just prior to the secondary impact, the impact force reaches a maximum of 91460 lbs. and this should be regarded as the maximum impact force for the near side drop analysis of the half model. The corresponding maximum acceleration for the 1/4 scale model is 312 g. which translates to a maximum acceleration of 78 g. for the full scale model. Figures 3.2.15 and 3.2.16 show the displacement and velocity time histories respectively of node 4539 which is near the center of gravity. Figures 3.2.17 and 3.2.18 show the displacements of the inner containment vessel and the outside corner of the RFTP opposite the impact point.

The time histories of hydrostatic stress for a selection of foam elements are plotted in figures 3.2.19. The foam is crushed the most in the top most area of the overpack body but at about 4 ms. these elements unload thus confirming completion of the initial impact before the secondary impact of the bottom portion of the overpack body occrus. Figures 3.2.20 to 3.2.23 are colour fringe plots depicting the hydrostatic stress in the overpack lid and body foam elements at times before and after the maximum impact force occurs (3 and 4 ms).

Effective plastic strain in the shell elements of the overpack lid, overpack body, and inner containment vessel are shown in figures 3.2.24 to 3.2.29 and the hydrostatic stress plots in figures 3.2.30 and 3.2.31 indicate whether the strains are compressive or tensile. The maximum strains of 23% (lid) are within acceptable limits. In the inner containment vessel, the highest strains occur at the bottom end of the container as a result of contact with the coarsely discretized bottom portion of the overpack body. Even so, the strains are low (below 3%) and the maximum hydrostatic stress is -30000 psi. (compression).

4.0 CONCLUSIONS

The results indicate that the structural integrity of the RFTP design is maintained during the 9m drops in the orientations considered herein. The modified RFTP overpack as designed appears to provide a good energy absorbing medium which effectively isolates the floating inner container and primary containment boundary from excessive damage.

Some interesting observations are apparent when comparing the impact response of the new RFTP design with the previous RFTP design/3/. In contrast to the previous design where the inner containment vessel was integral with the overpack, the current design has a floating inner container separate from the overpack. This puts a higher demand on the overpack lid and connecting bolts during edge drops since the component of load exerted by the inner container in the direction of the package longitudinal axis must be resisted totally by the lid bolts. While the lid bolts are stretched during the edge drop, in view of their strength and ductility, no gross separation of the overpack lid from the body is expected.

The outcome of the analyses conducted on the modified RFTP design, leads to the conclusion that for the impact scenarios investigated the overpack provides good impact resistance and the inner container structural integrity is not compromised. The current overpack lid design provides excellent resistance against shearing forces across the lid unlike the previous design where a small spigot was used for this purpose.

Areas where improvement of the design would lead to increased safety factors are:

i) increase the number and/or size of overpack lid bolts to minimize separation of the overpack lid from the body;

ii) increase the clearance between the lid bolts and the lid bolt holes to preclude premature shearing of the bolts;

iii) modify overpack lid bolt shank so that the root diameter of the thread is greater than the shank to reduce the possibility of localized failure near the threads.

5.0 RETRIEVAL OF COMPUTER FILES

This analysis was carried out using the VAX computer facility in the Applied Mechanics Section of the Mechanical Research Department at Ontario Hydro. The computer files related to this project have been stored on tape in VMS BACKUP format. A log of the backup procedure is given in Appendix A5.

6.0 ACKNOWLEDMENTS

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Radioactive Filter Transportation Package

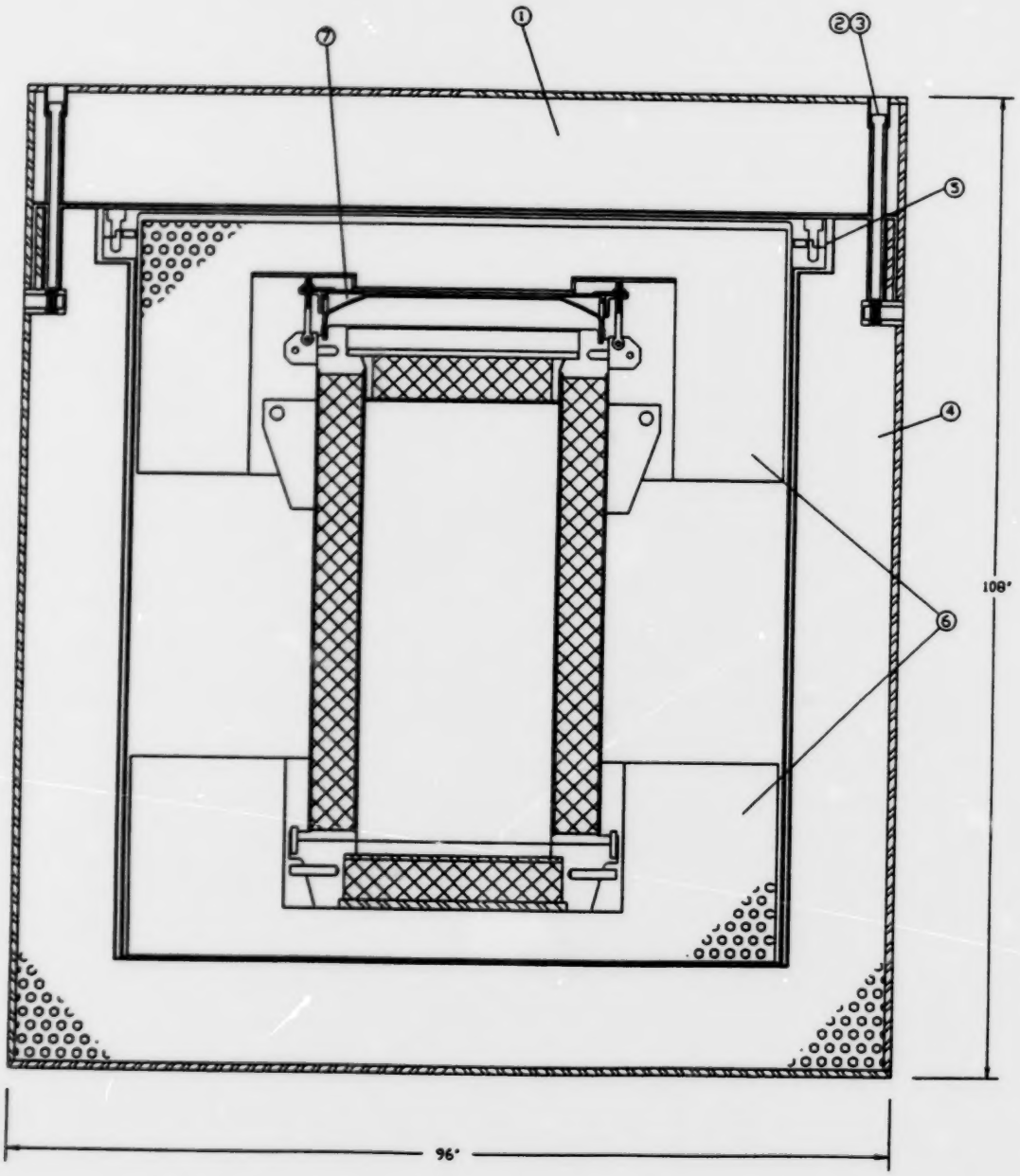


FIGURE 1.1
RFTP ASSEMBLY

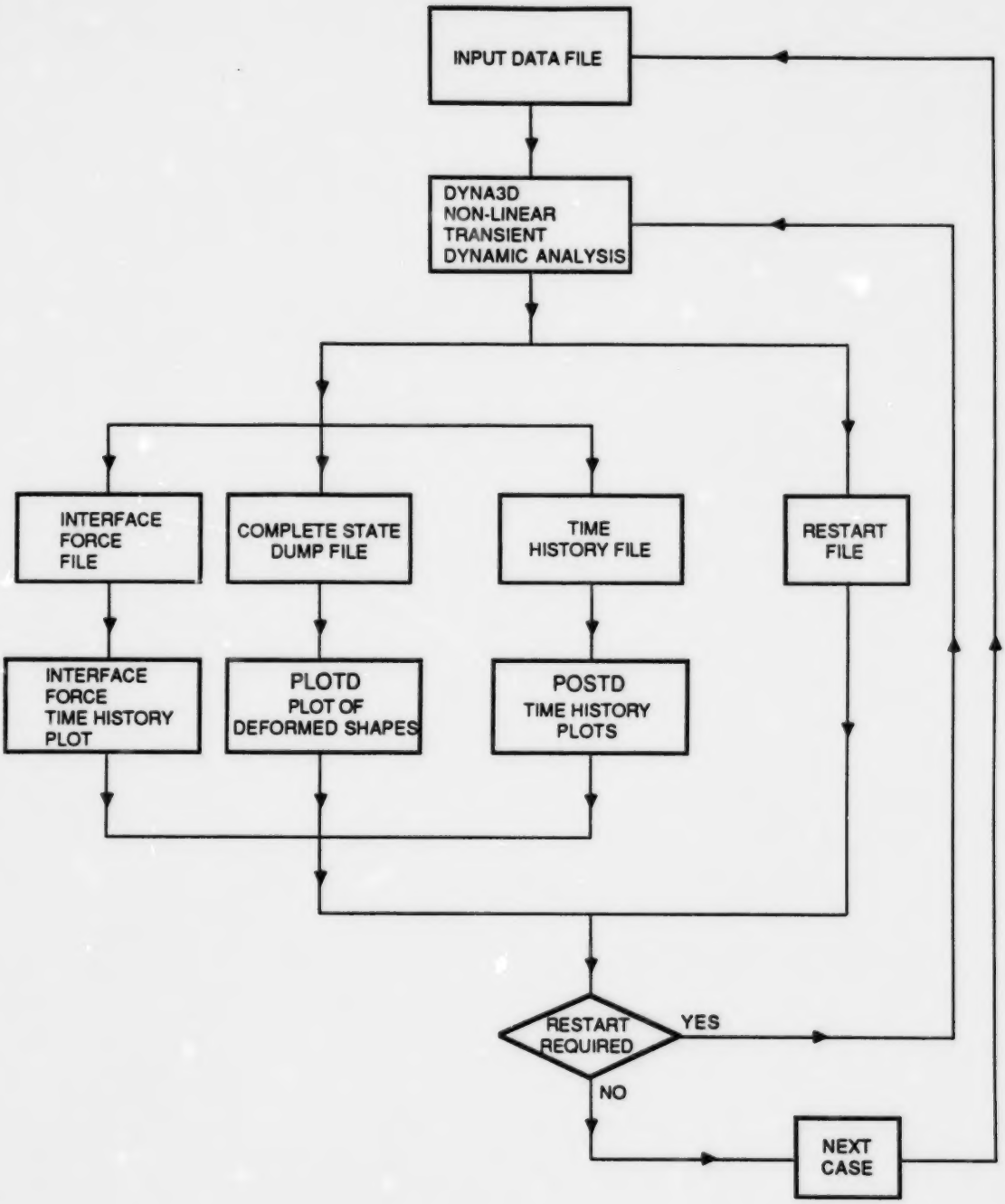


FIGURE 2.1.1

FLOW CHART OF COMPUTATIONAL SEQUENCE

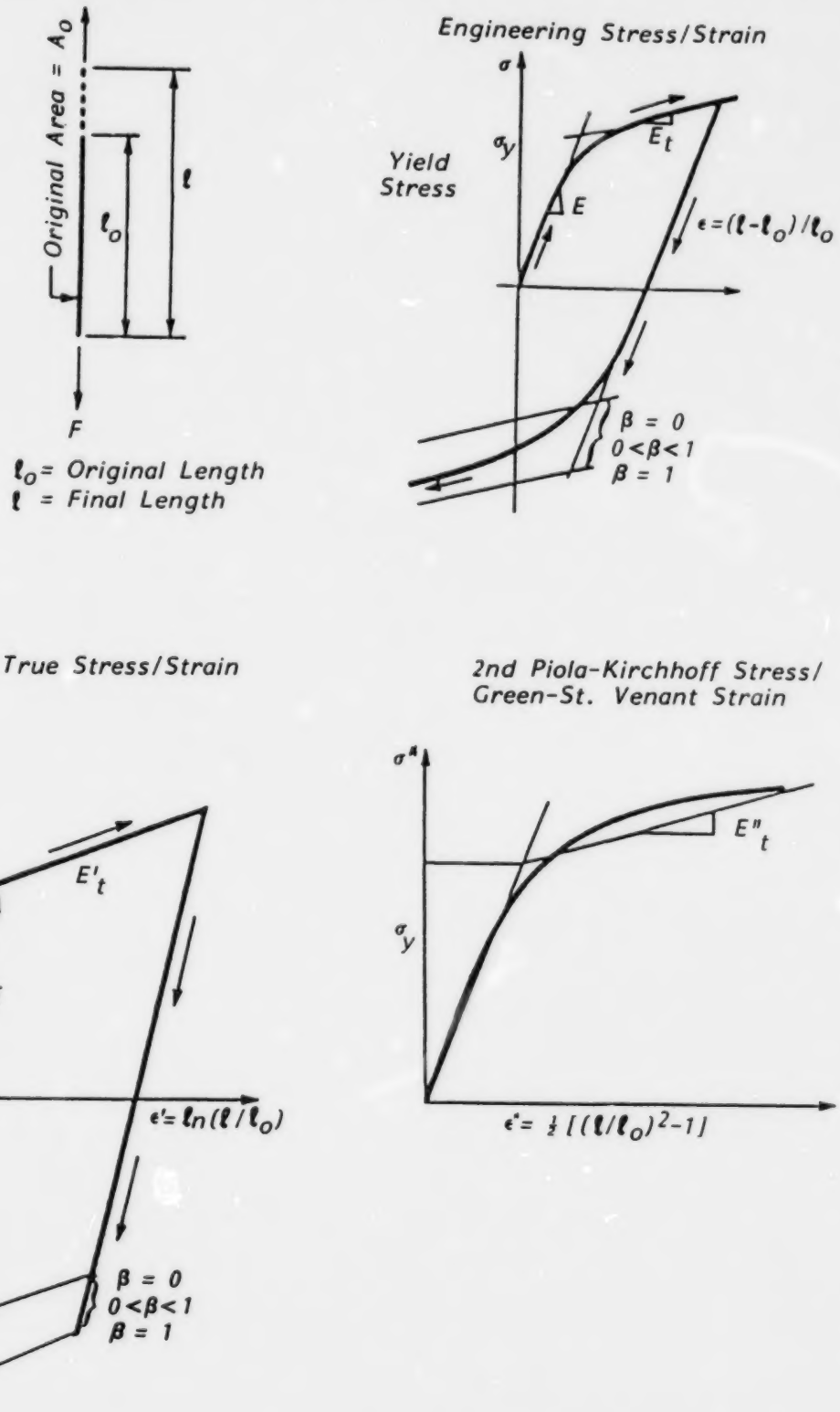


FIGURE 2.2.1
STRESS/STRAIN MEASURES
ELASTO-PLASTIC MATERIAL MODELS

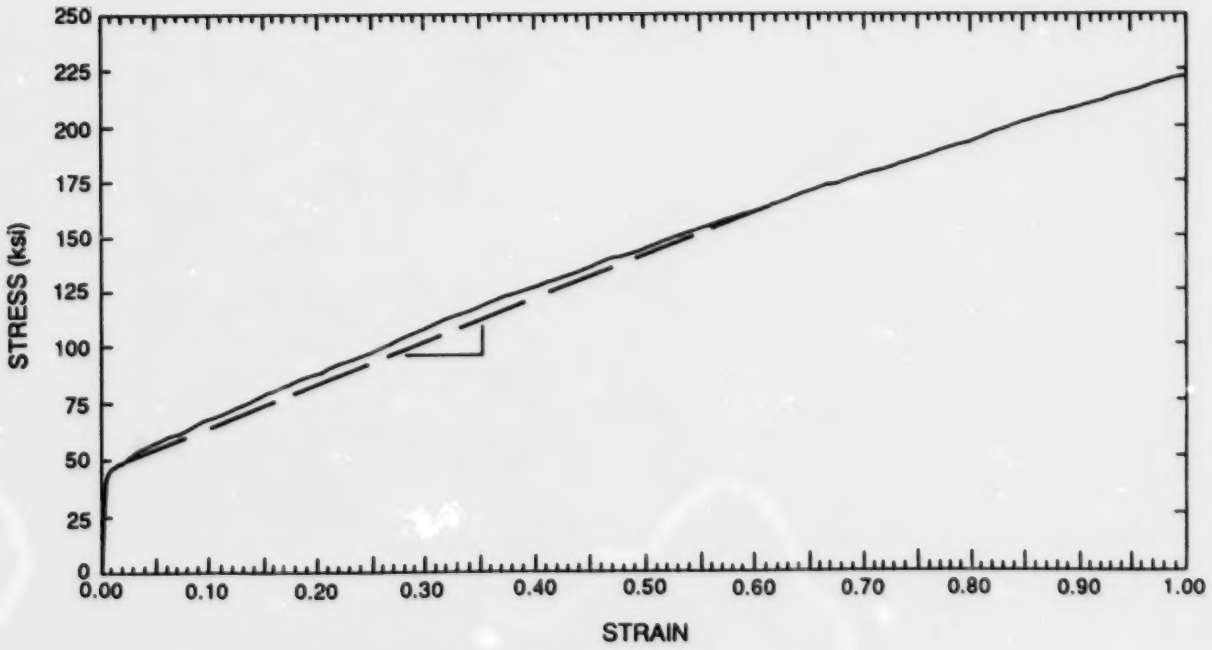


FIGURE 2.2.2

STRESS / STRAIN CURVE FOR 304L STAINLESS STEEL MODEL

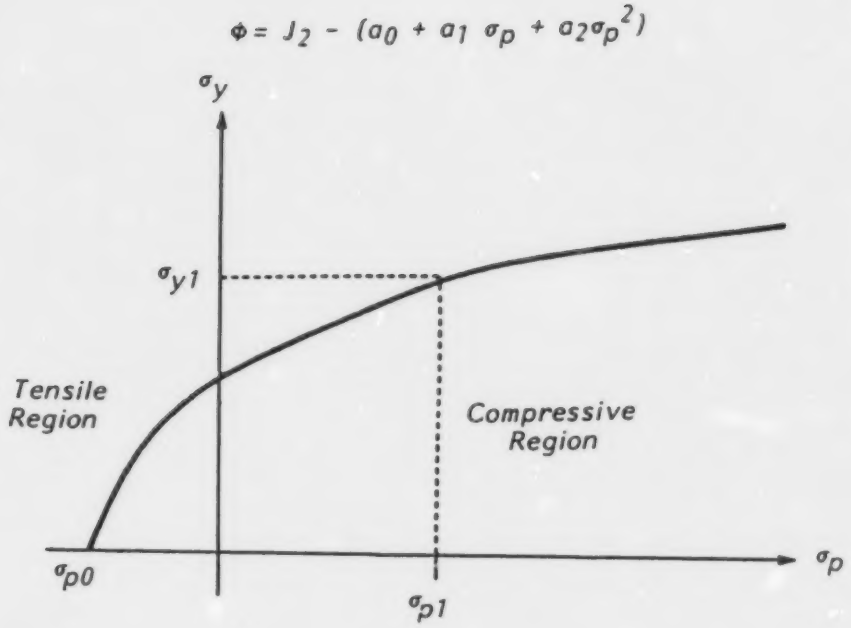


FIGURE 2.2.3
POLYURETHANE FOAM MODEL
PRESSURE VERSUS YIELD STRESS CURVE

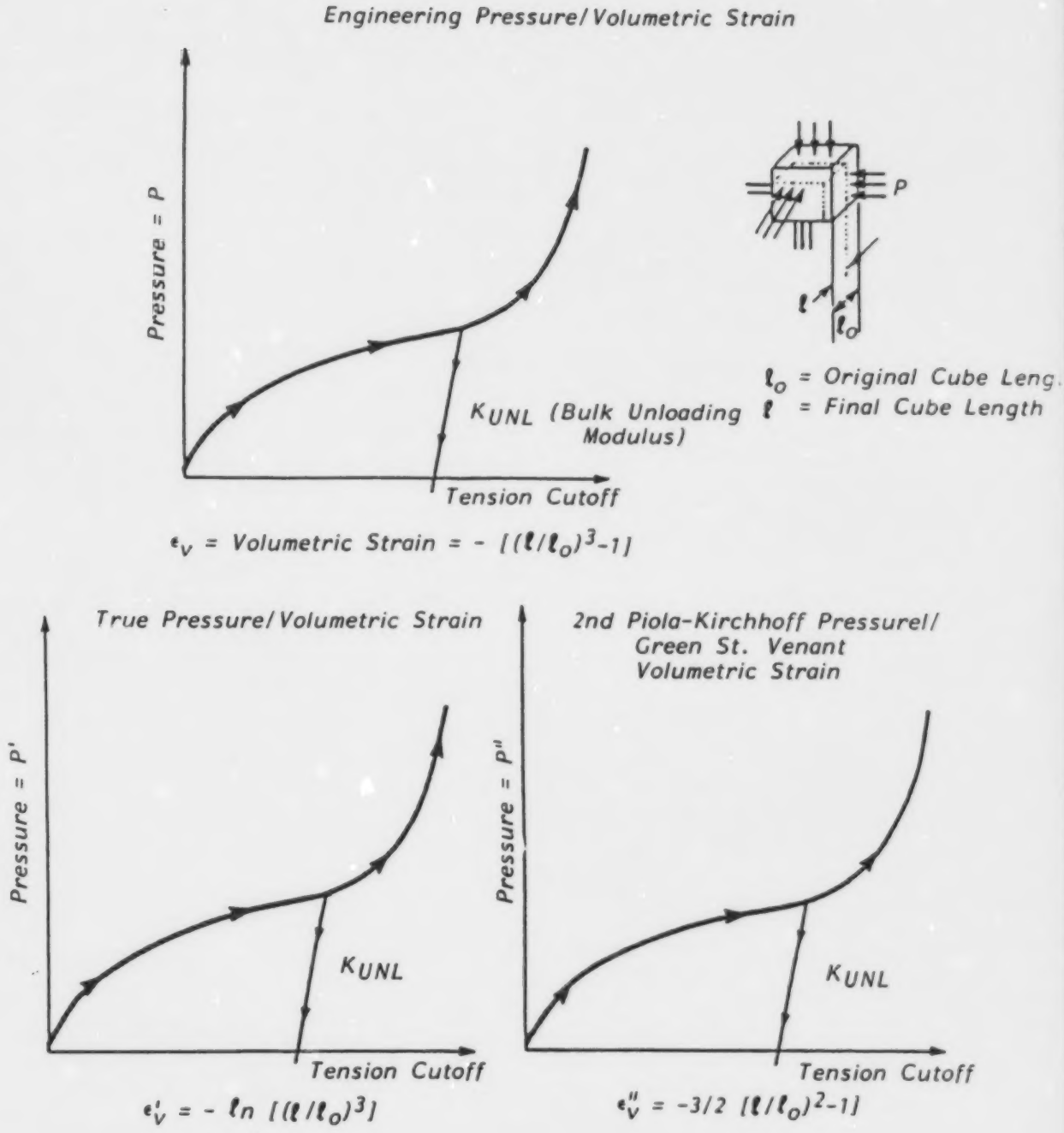


FIGURE 2.2.4
PRESSURE/VOLUMETRIC STRAIN MEASURES
CRUSHABLE FOAM MATERIAL MODEL

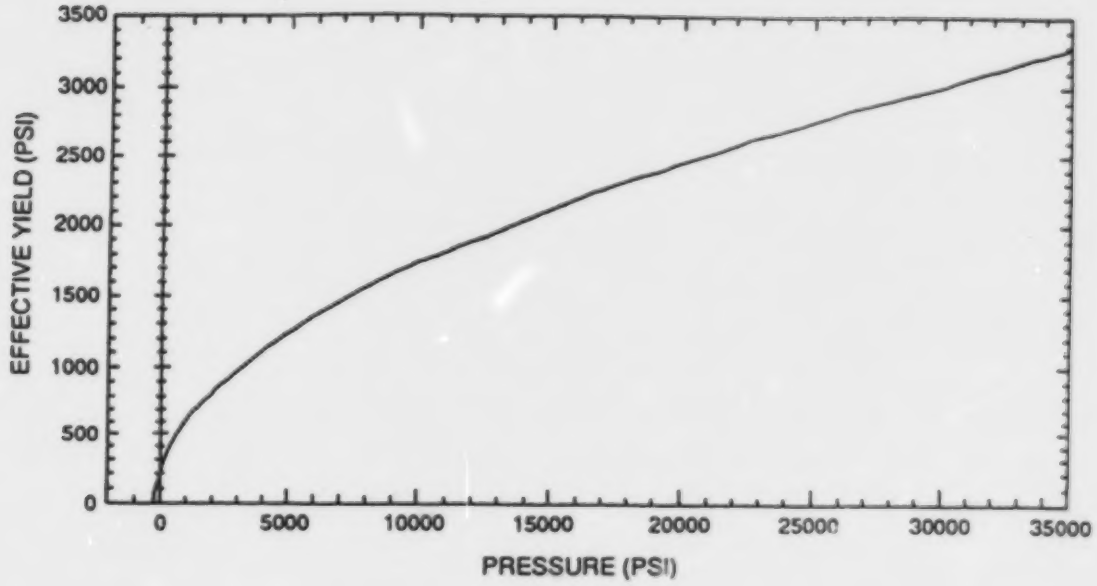


FIGURE 2.2.5
YIELD VS PRESSURE CURVE FOR
POLYURETHANE FOAM MODEL

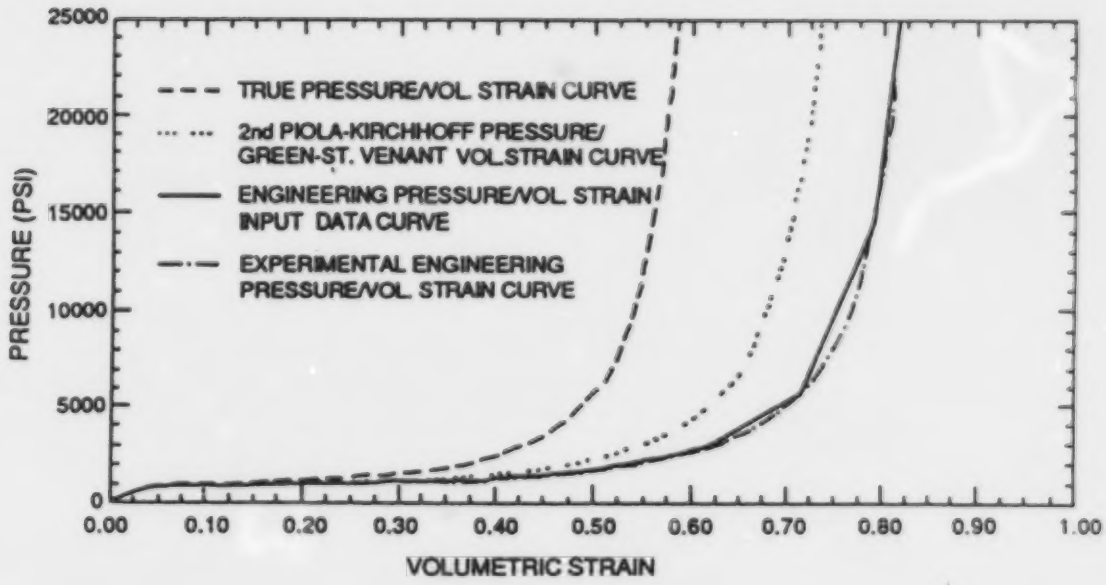


FIGURE 2.2.6
PRESSURE/VOLUMETRIC STRAIN CURVE FOR
POLYURETHANE FOAM MODEL

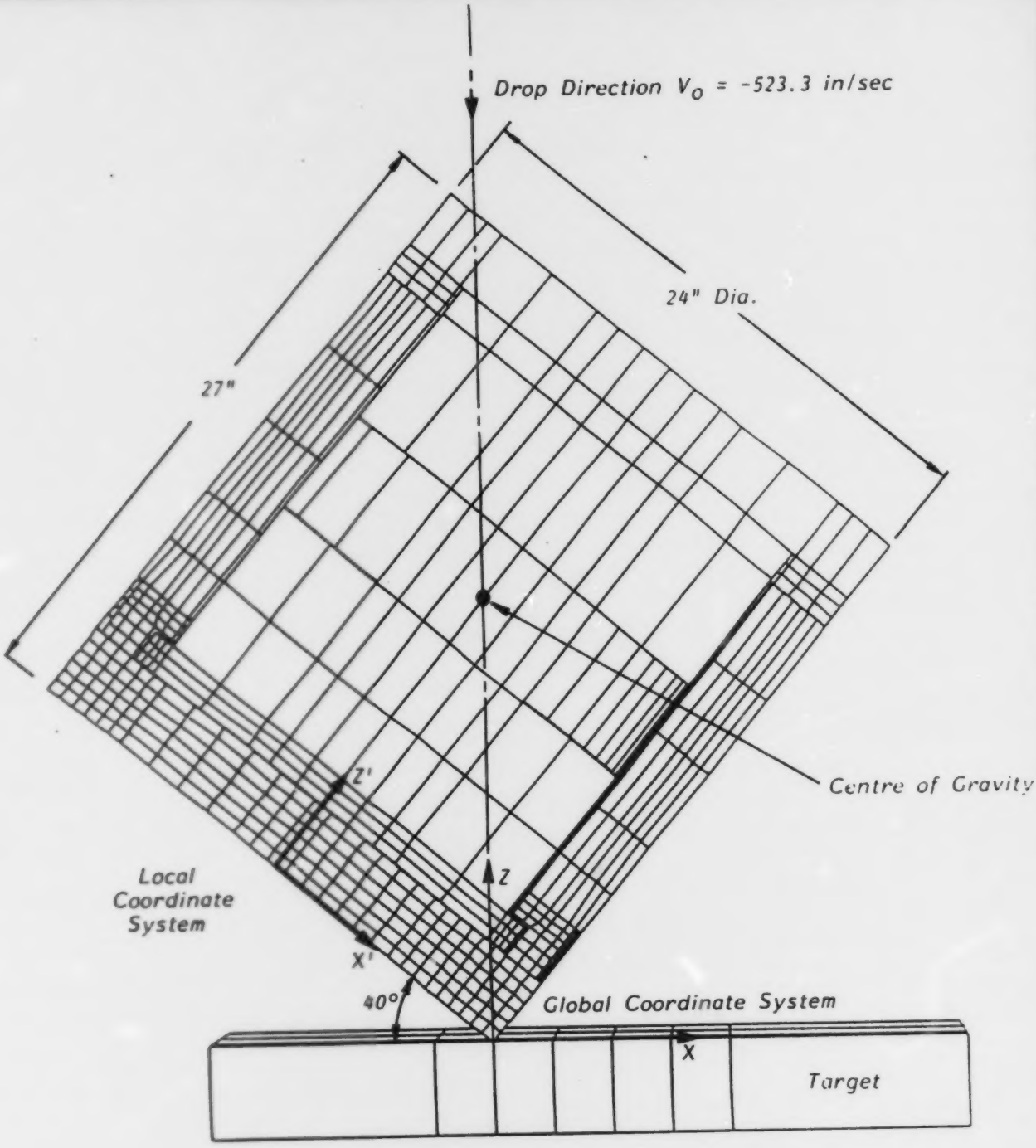


FIGURE 2.3.1
RFTP MODEL CONFIGURATION FOR 9 m TOP DOWN EDGE DROP

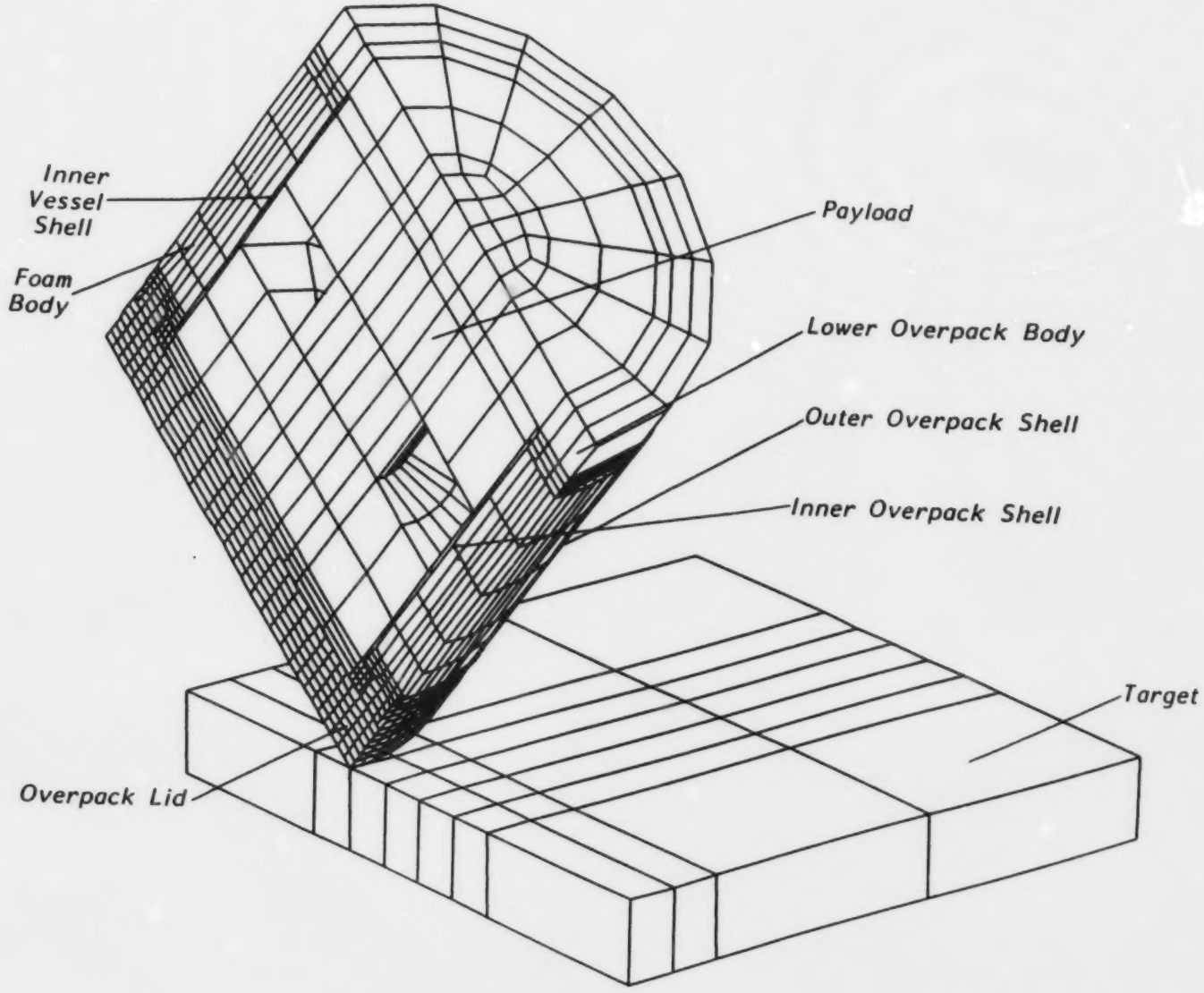


FIGURE 2.3.2
RFTP OVERALL MODEL GEOMETRY

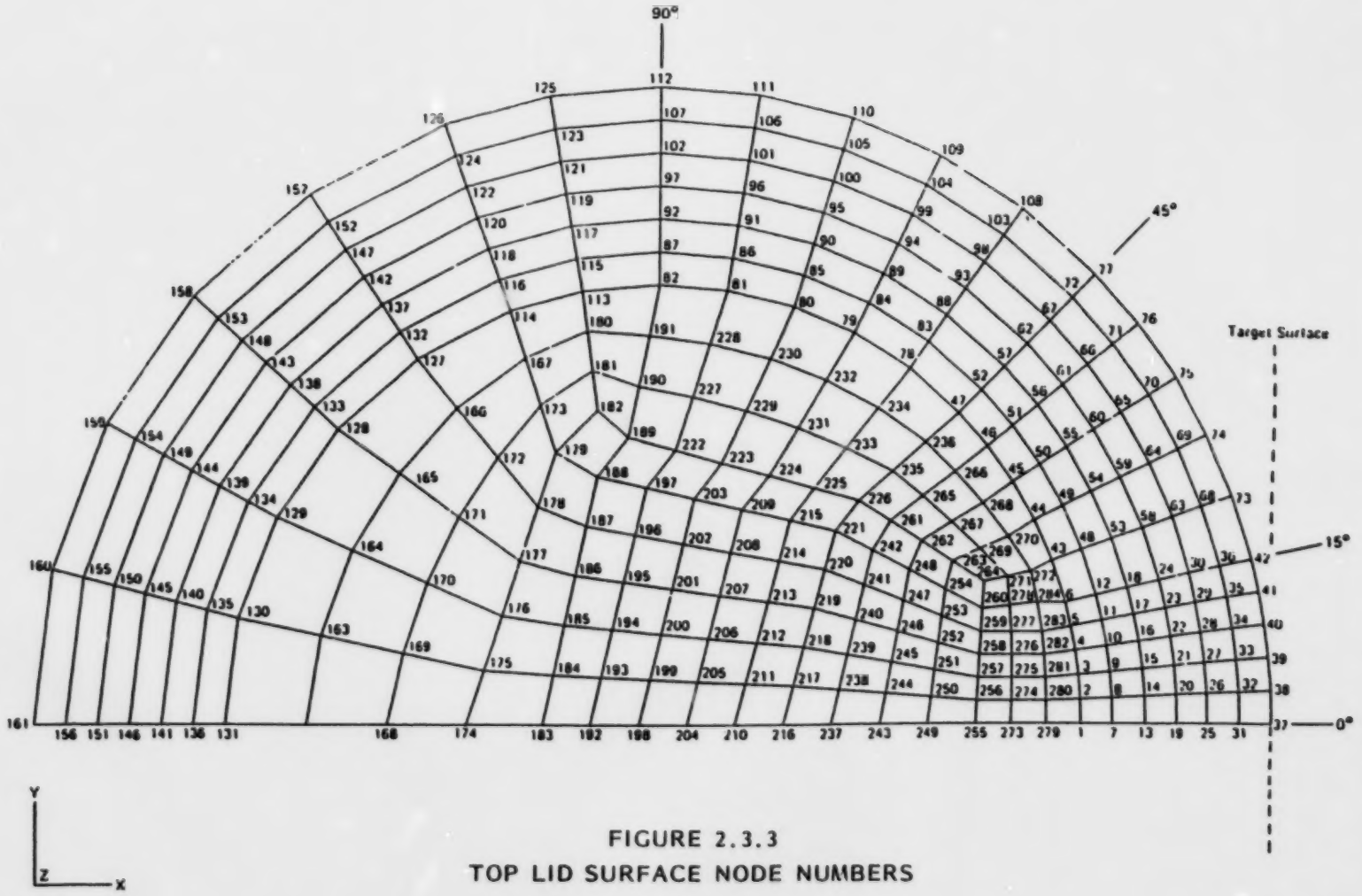


FIGURE 2.3.3
TOP LID SURFACE NODE NUMBERS

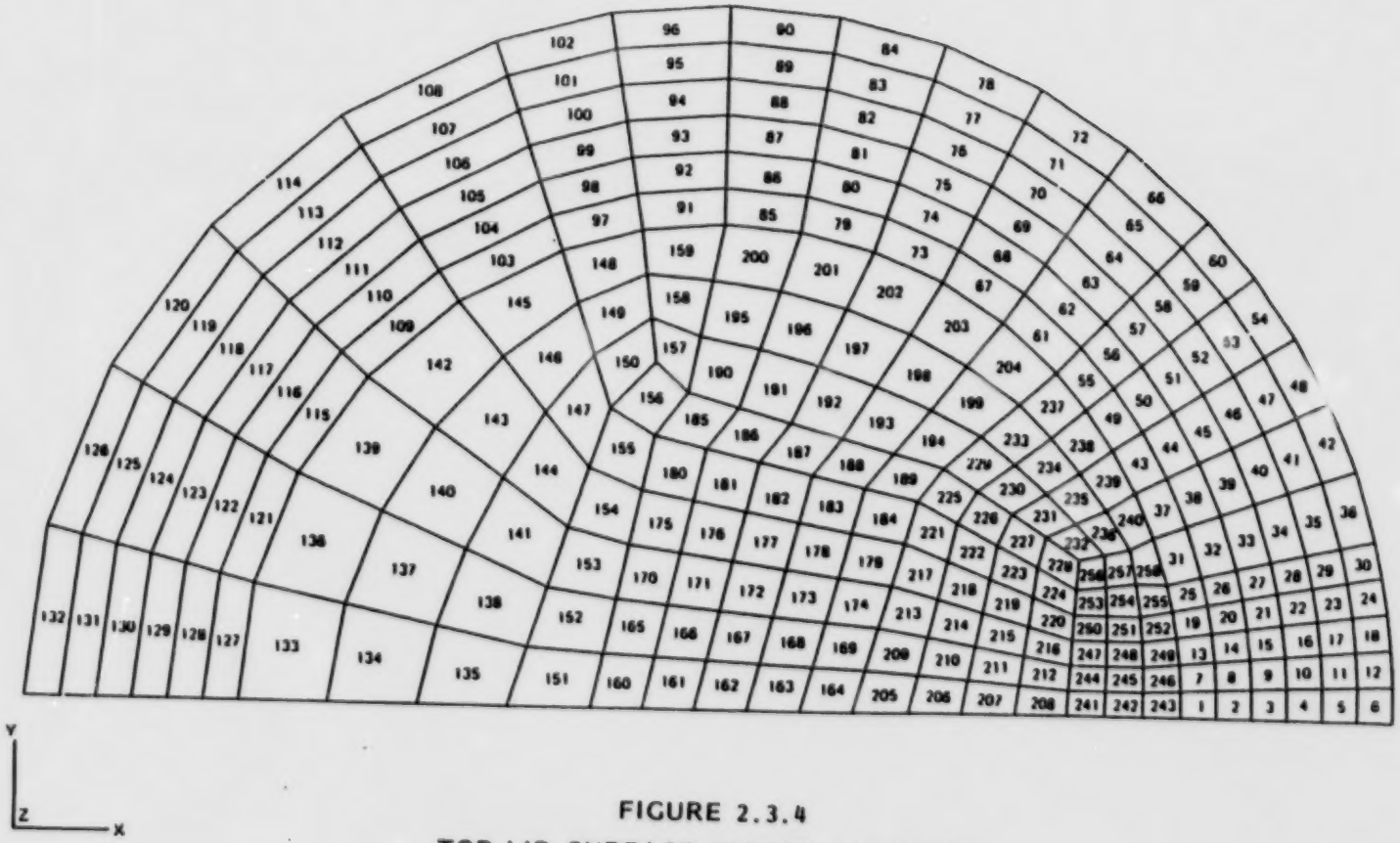
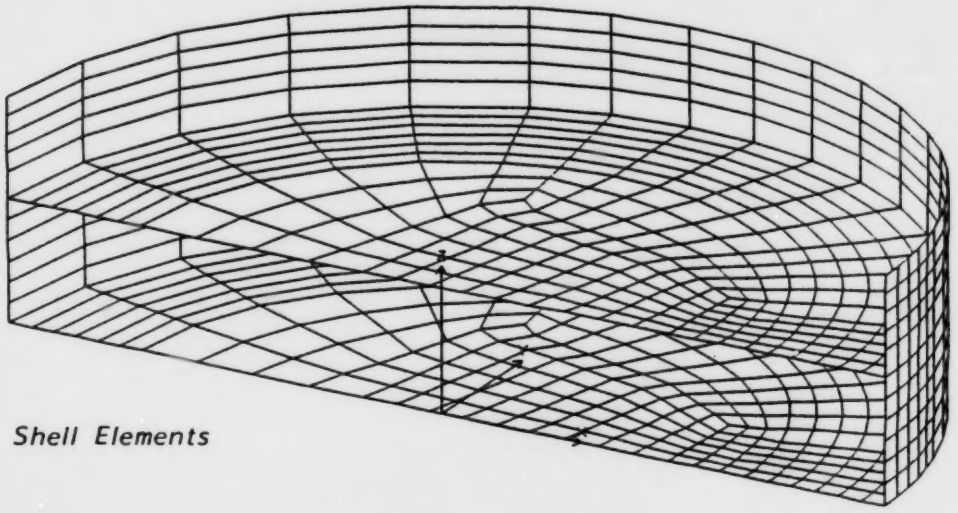
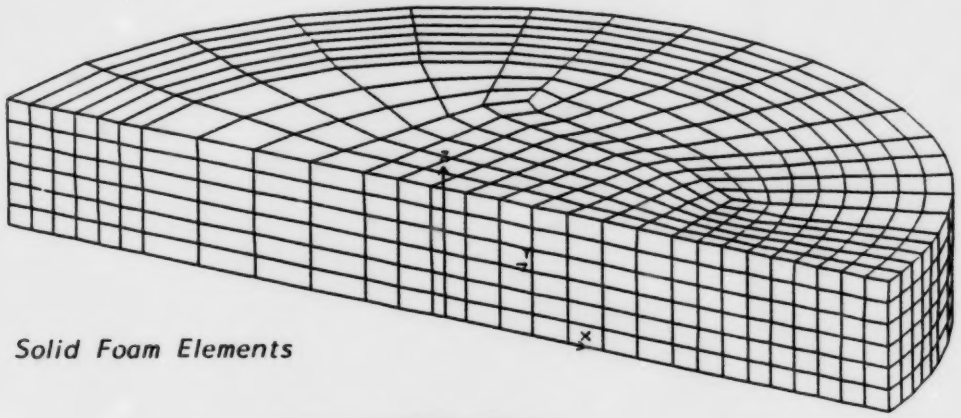


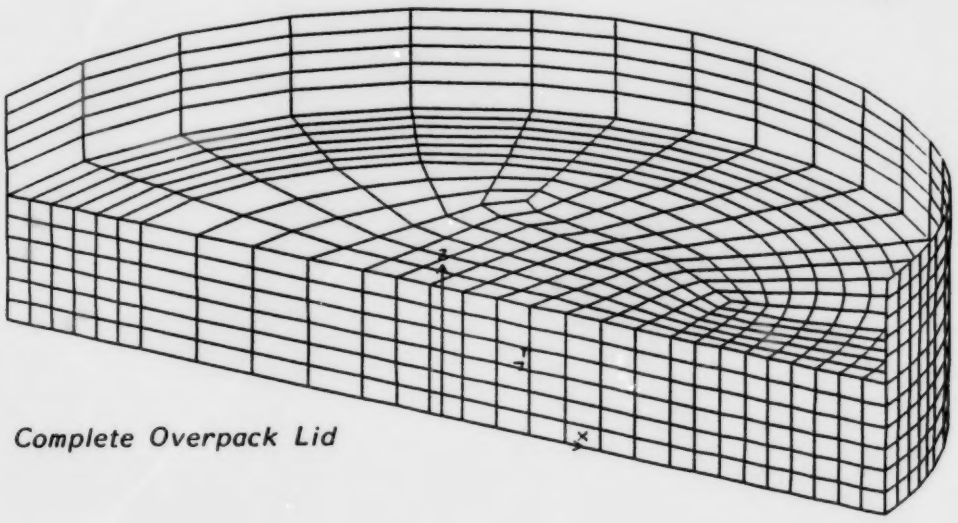
FIGURE 2.3.4
TOP LID SURFACE ELEMENT NUMBERS



Shell Elements



Solid Foam Elements



Complete Overpack Lid

FIGURE 2.3.5
OVERPACK LID ELEMENTS

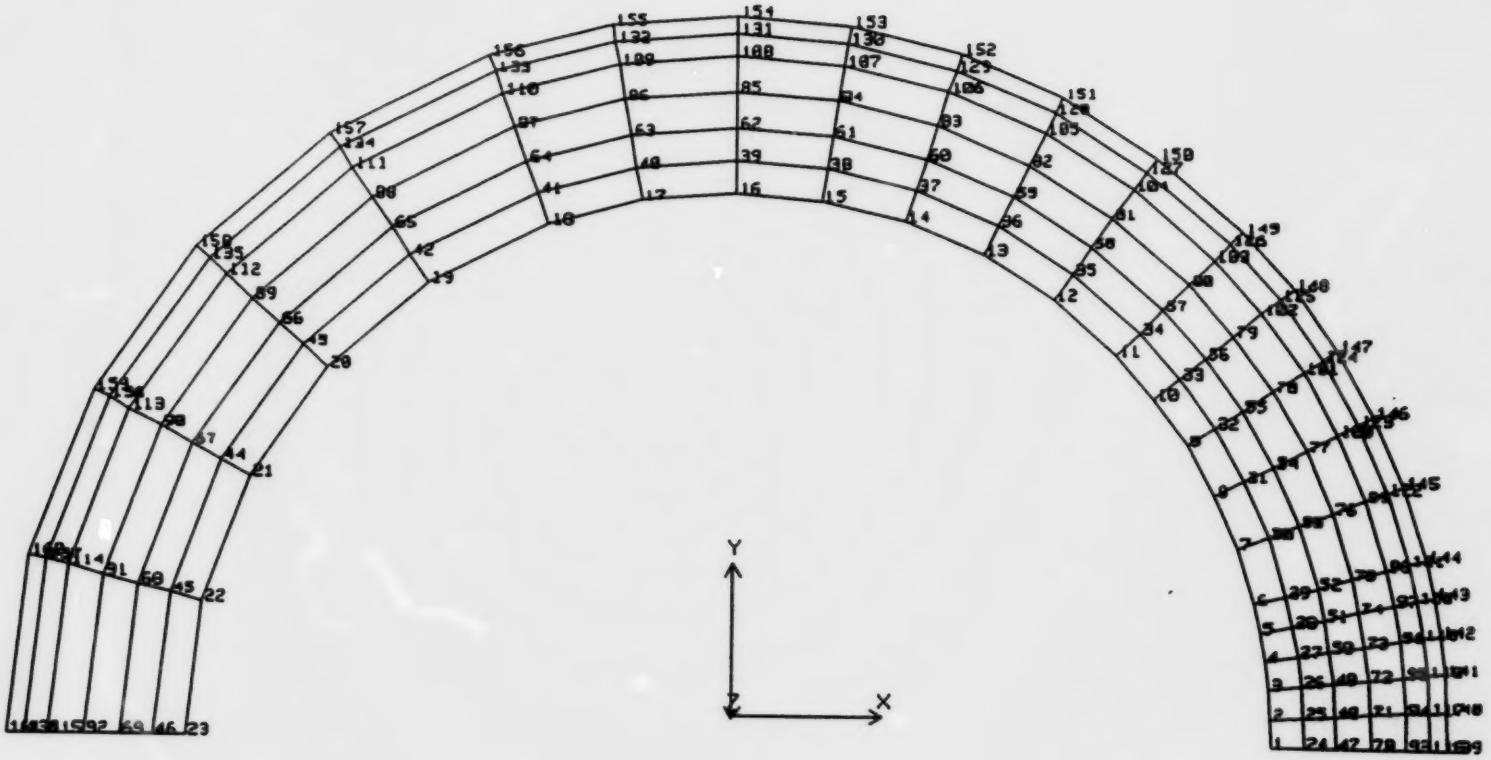


FIGURE 2.3.6
OVERPACK BODY GRID NODE NUMBERS

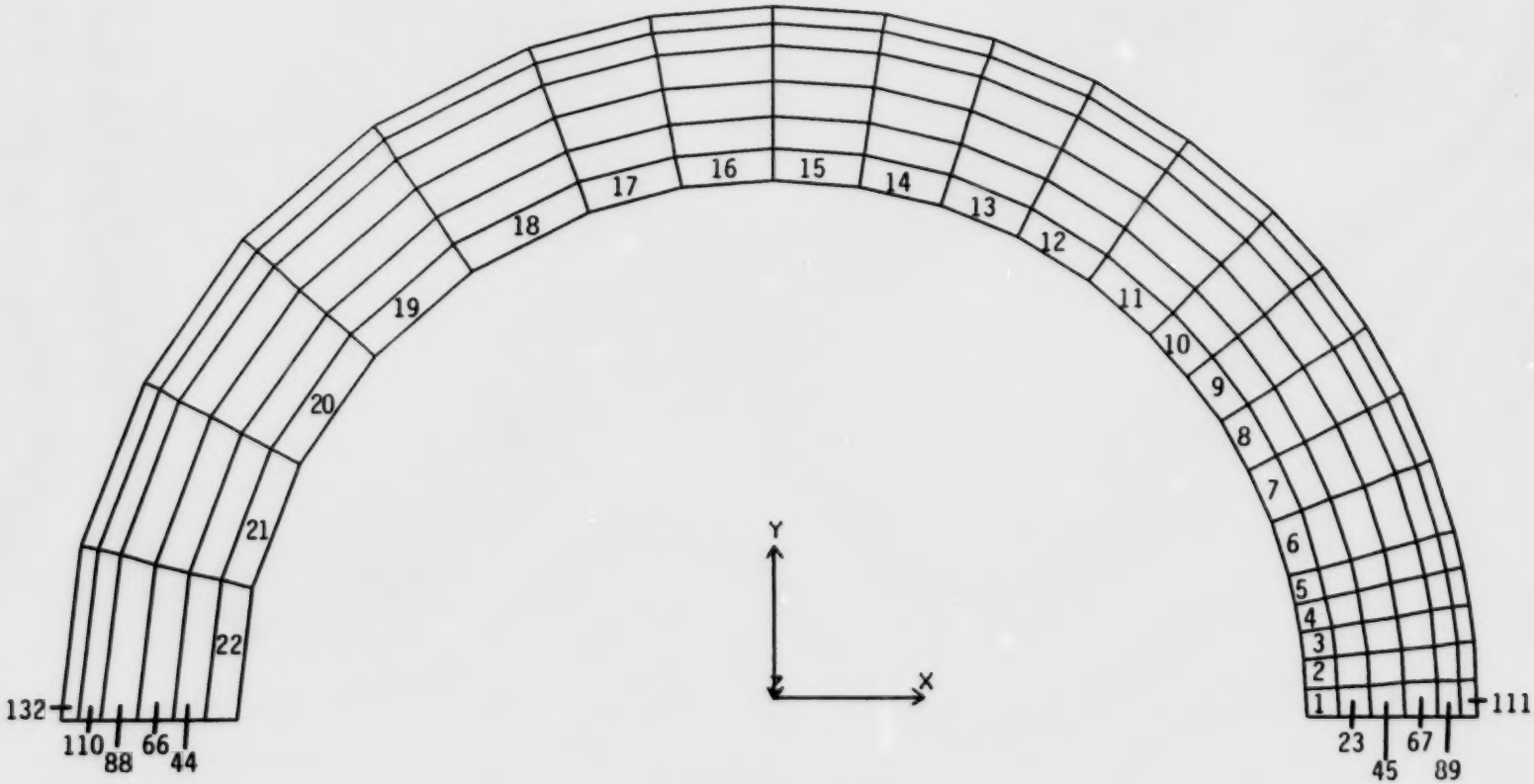


FIGURE 2.3.7
OVERPACK BODY GRID ELEMENT NUMBERS

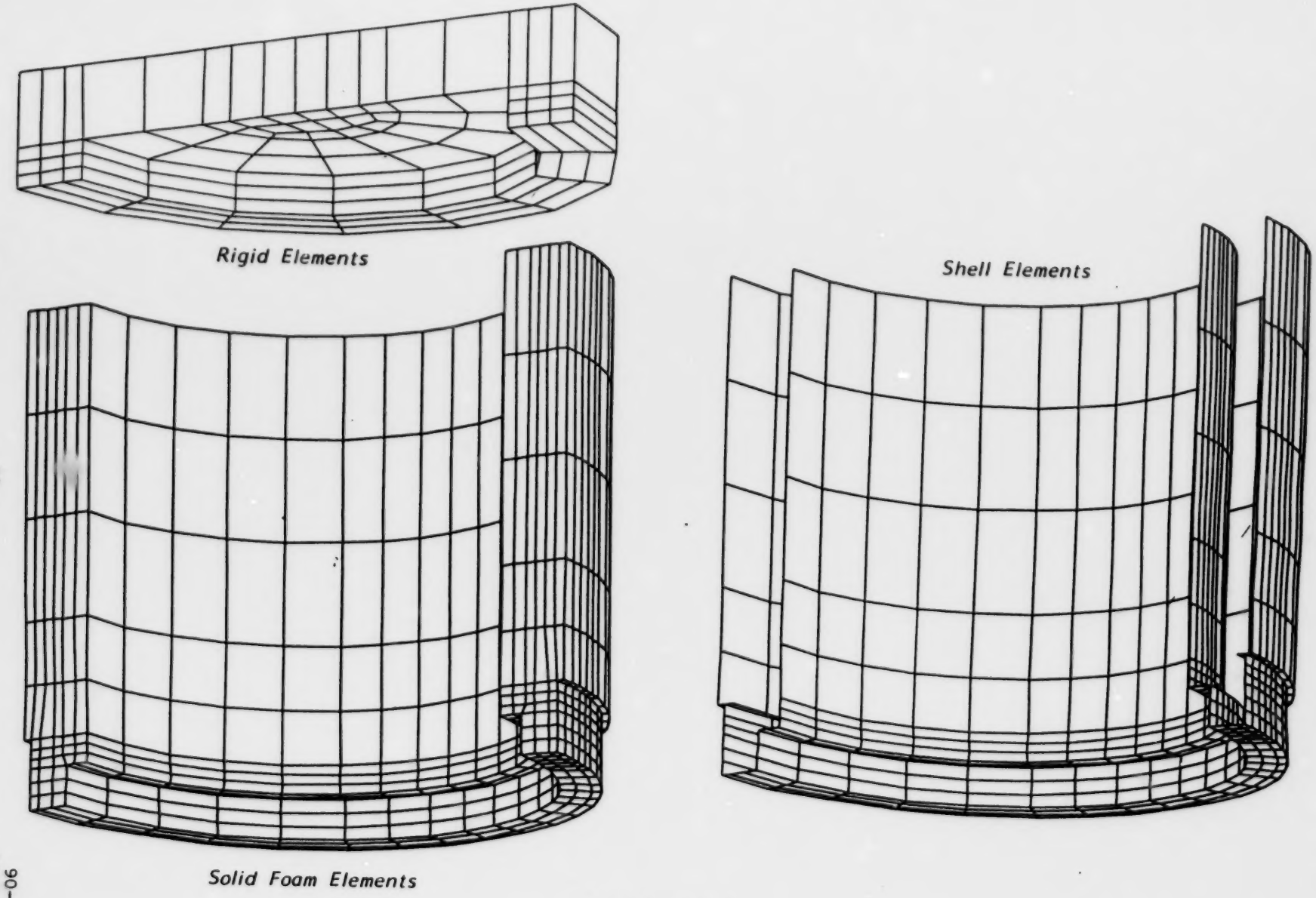


FIGURE 2.3.8
OVERPACK BODY SHELL AND SOLID ELEMENTS

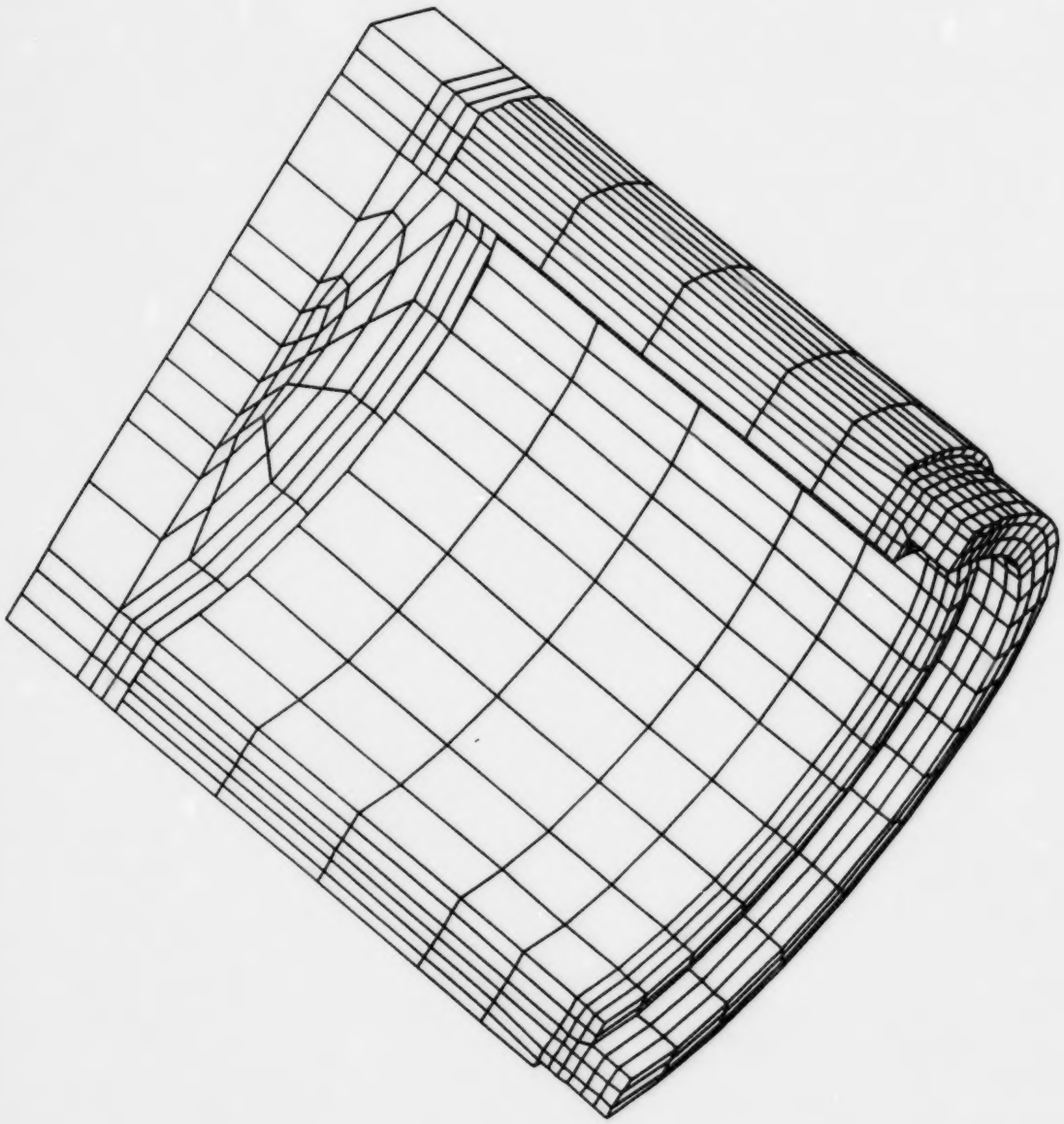


FIGURE 2.3.9
OVERPACK BODY ELEMENTS

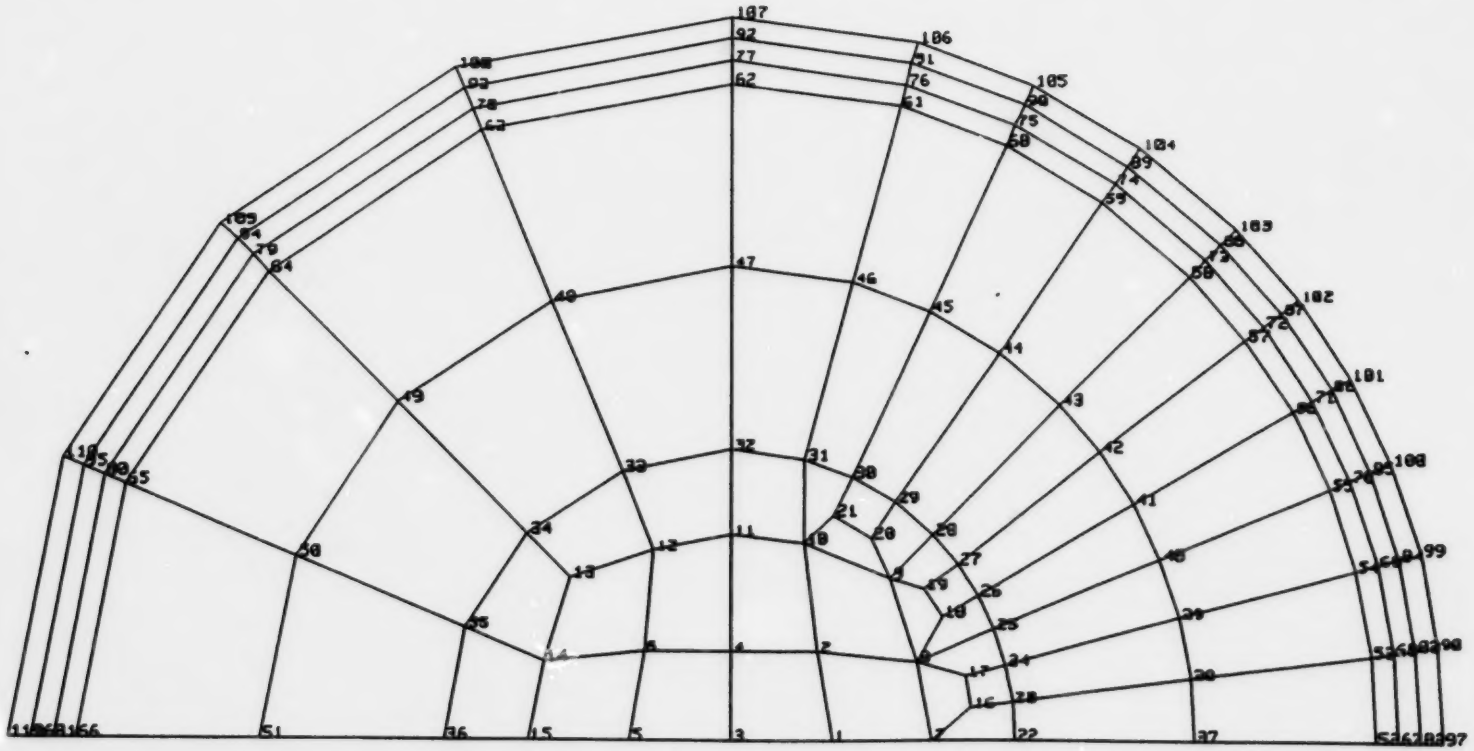


FIGURE 2.3.10
INNER VESSEL GRID NODE NUMBERS

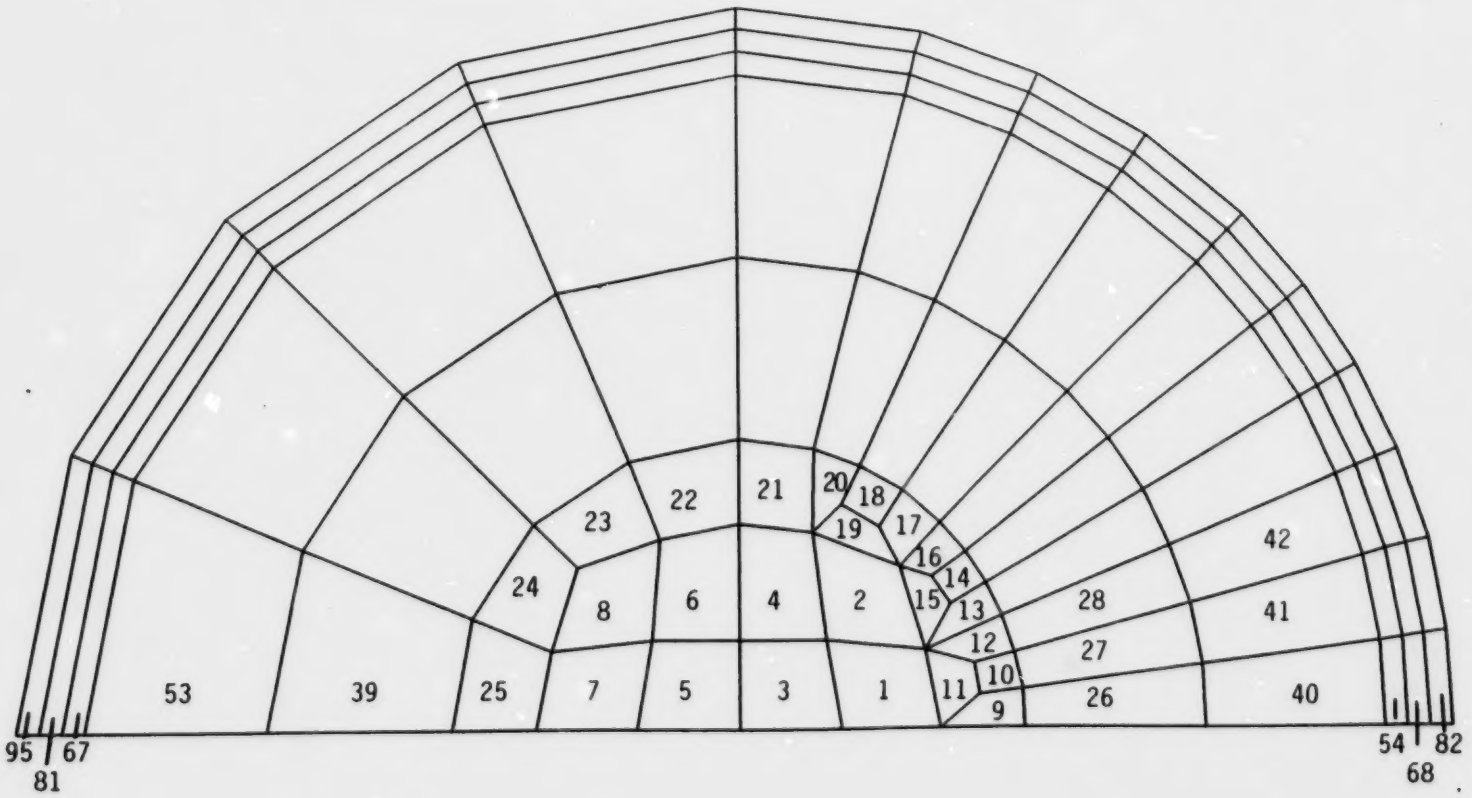


FIGURE 2.3.11

INNER VESSEL GRID ELEMENT NUMBERS

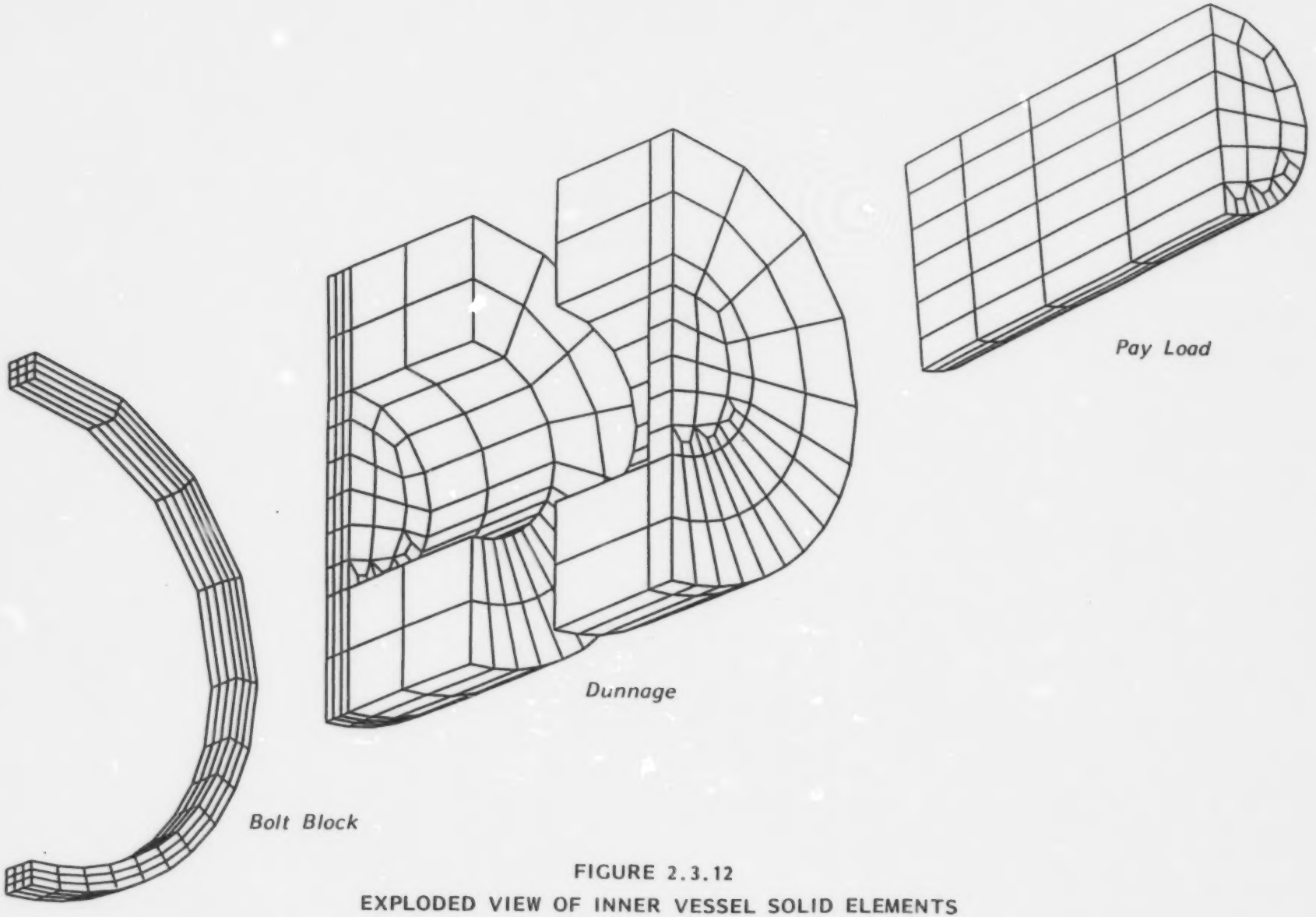


FIGURE 2.3.12
EXPLODED VIEW OF INNER VESSEL SOLID ELEMENTS

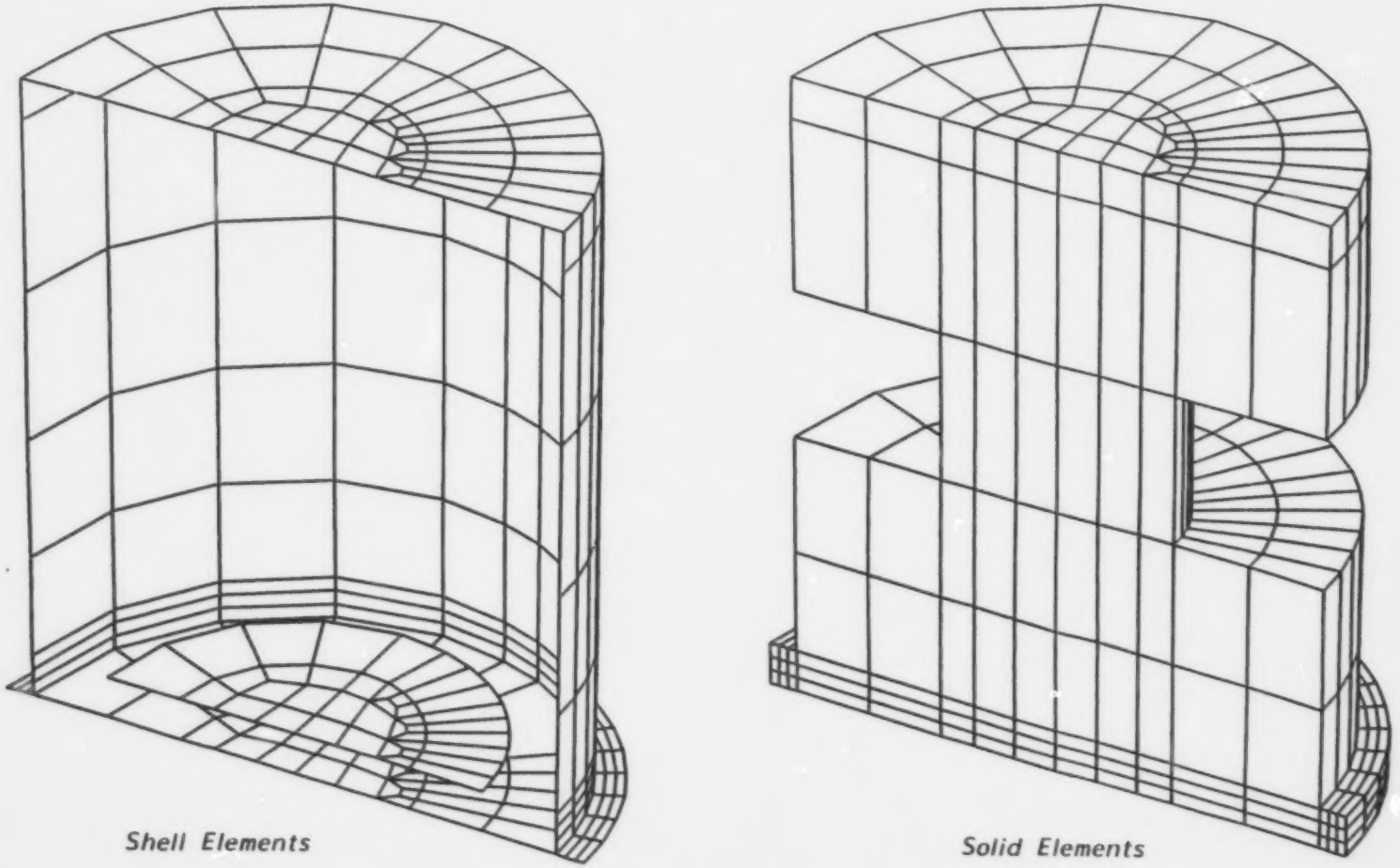


FIGURE 2.3.13
INNER VESSEL SHELL AND SOLID ELEMENTS

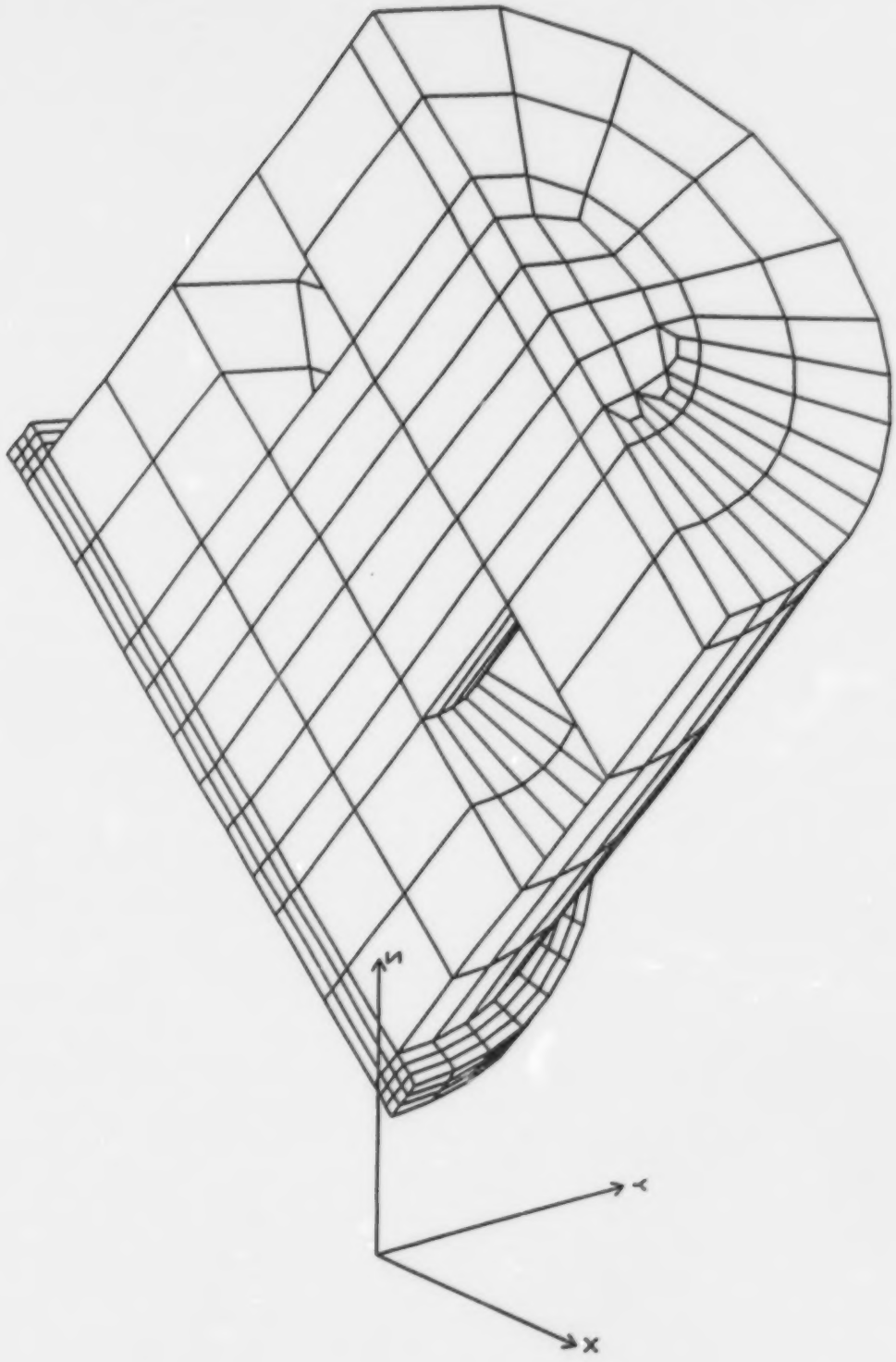


FIGURE 2.3.14
INNER VESSEL ELEMENTS

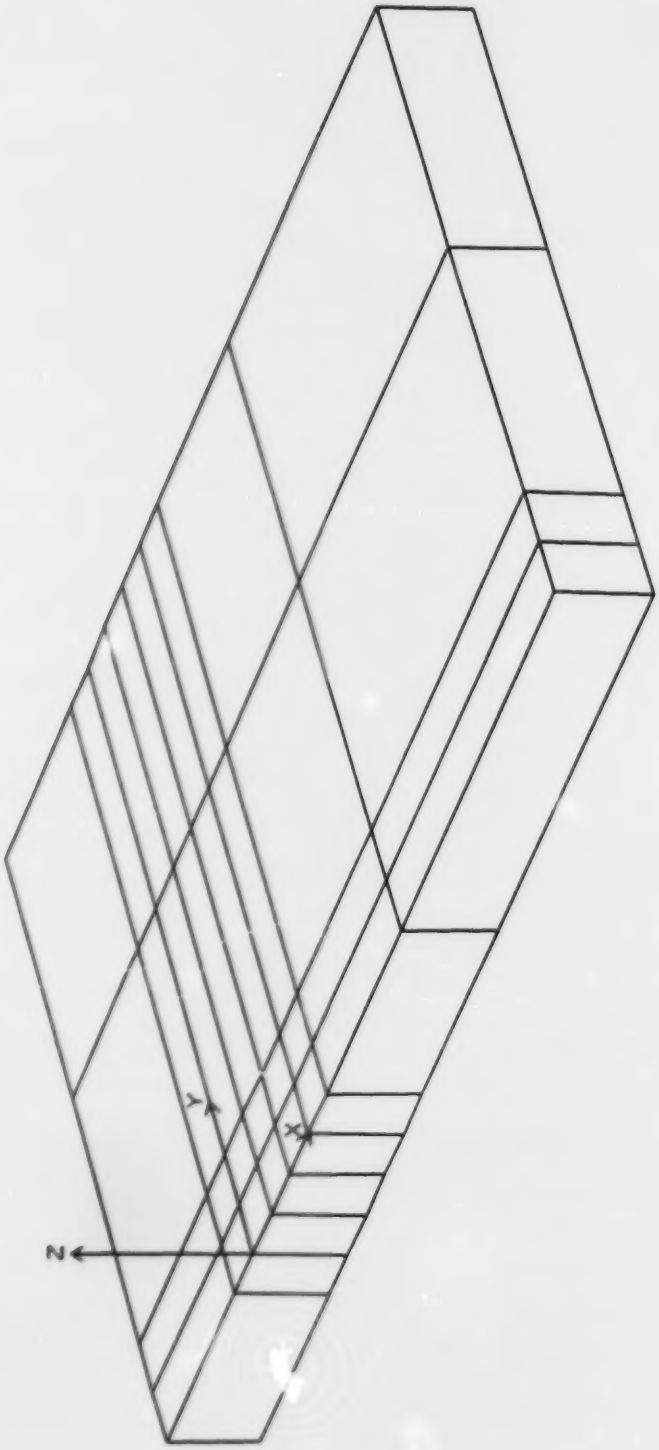


FIGURE 2.3.15
TARGET ELEMENTS

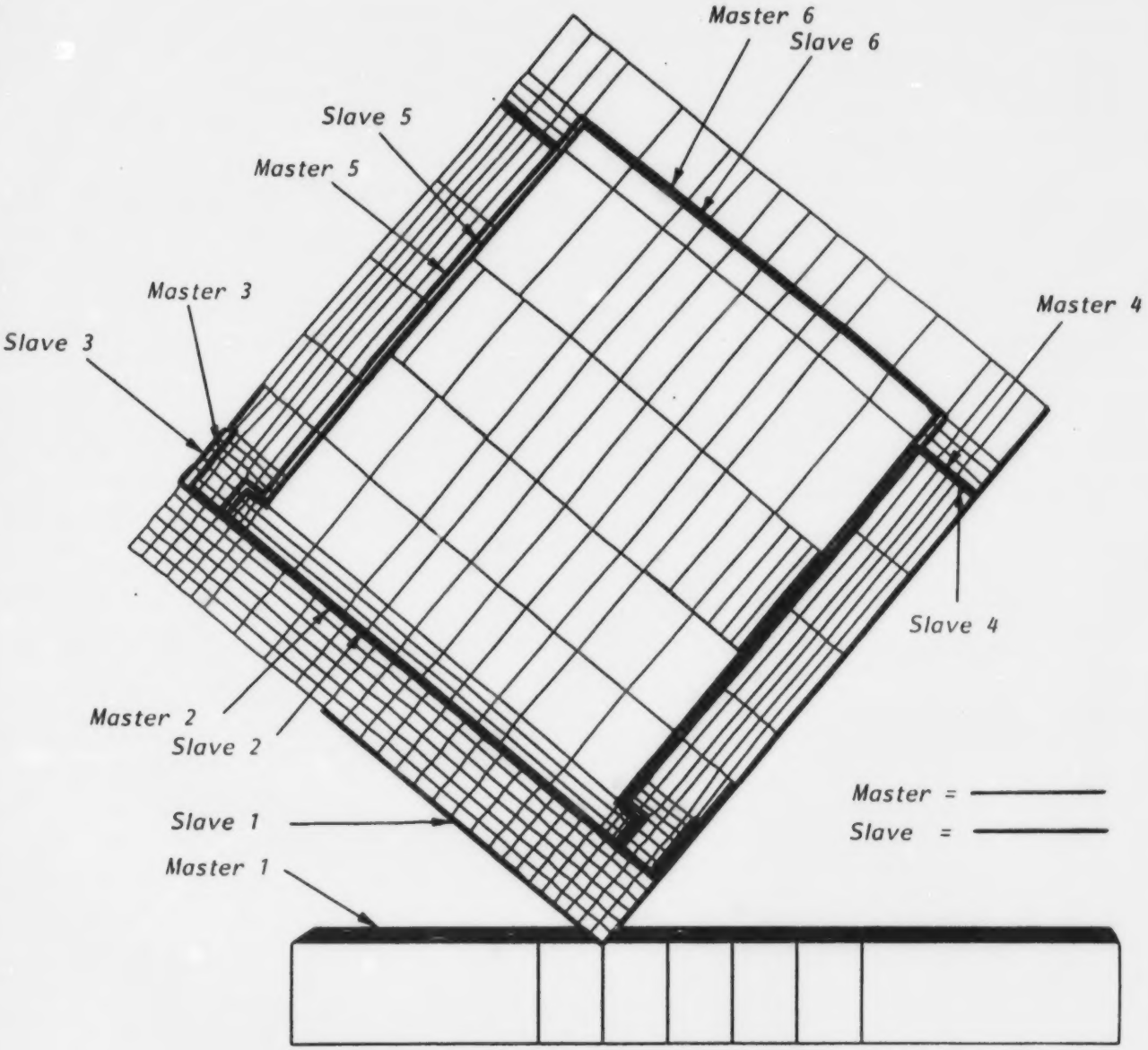


FIGURE 2.3.16
MASTER/SLAVE SURFACES

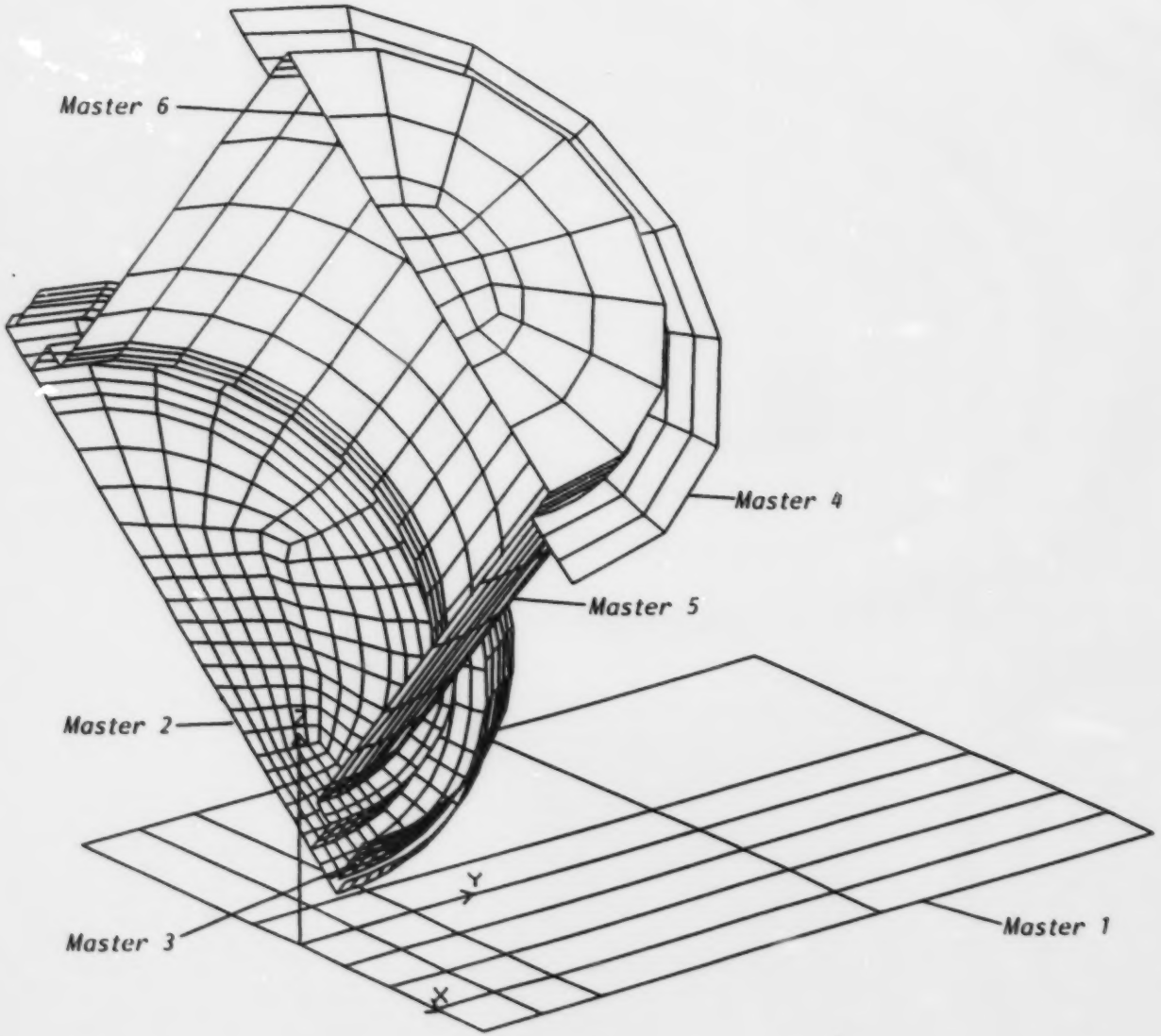


FIGURE 2.3.17
MASTER SURFACES

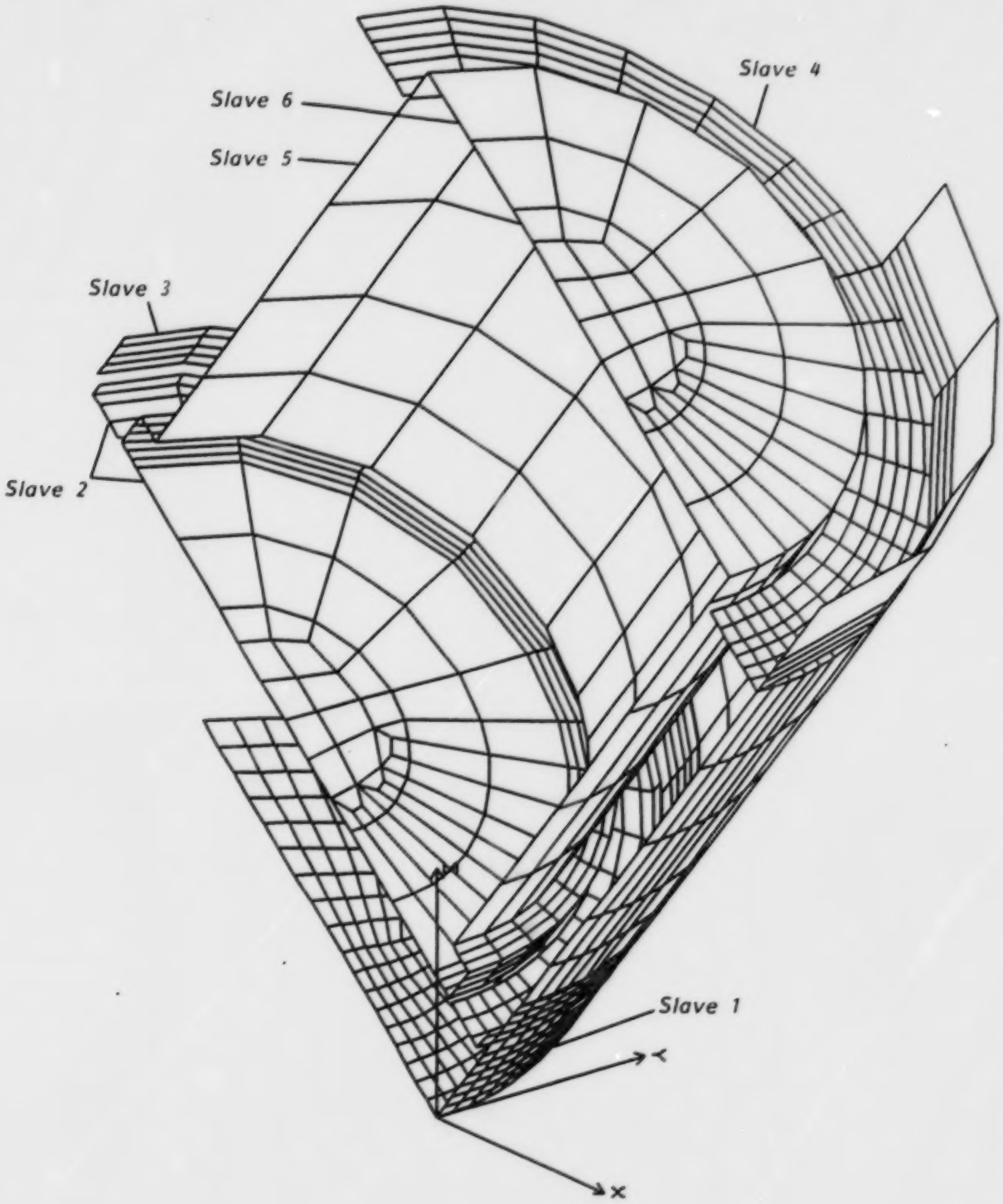


FIGURE 2.3.18
SLAVE SURFACES

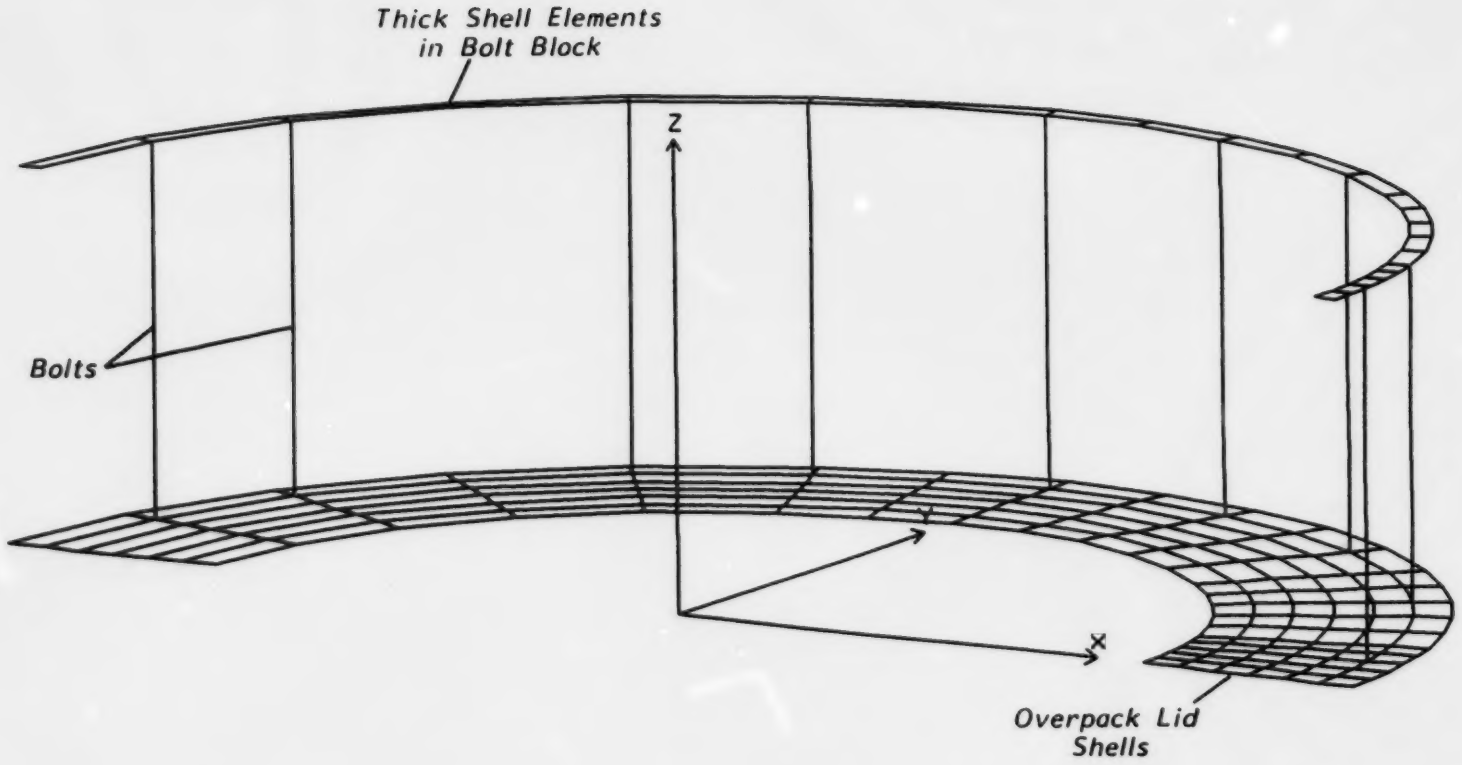


FIGURE 2.3.19
OVERPACK LID CONNECTING BOLT ELEMENTS

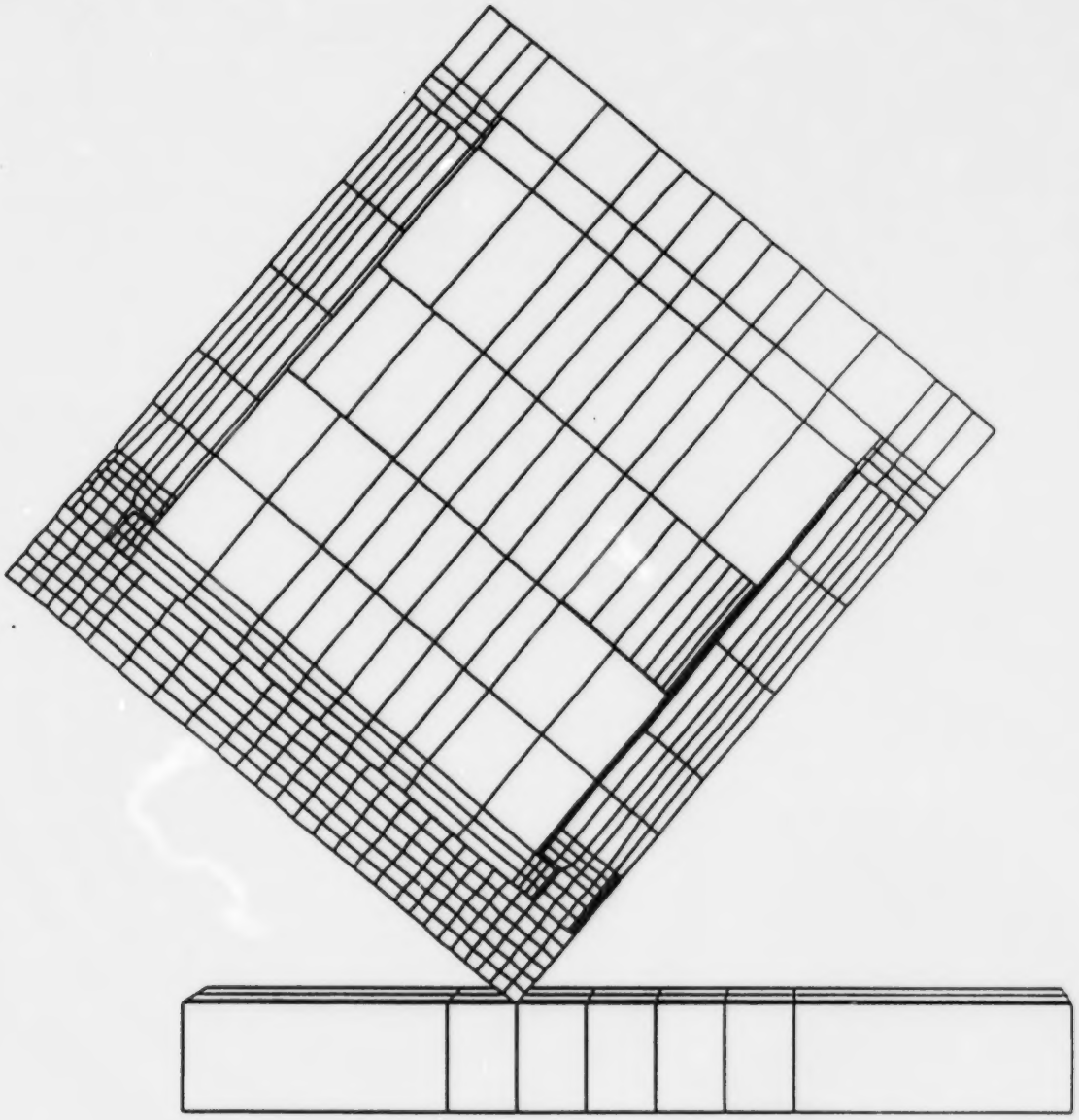


FIGURE 3.1.1
RFTP UNDEFORMED GEOMETRY (SIDE VIEW)

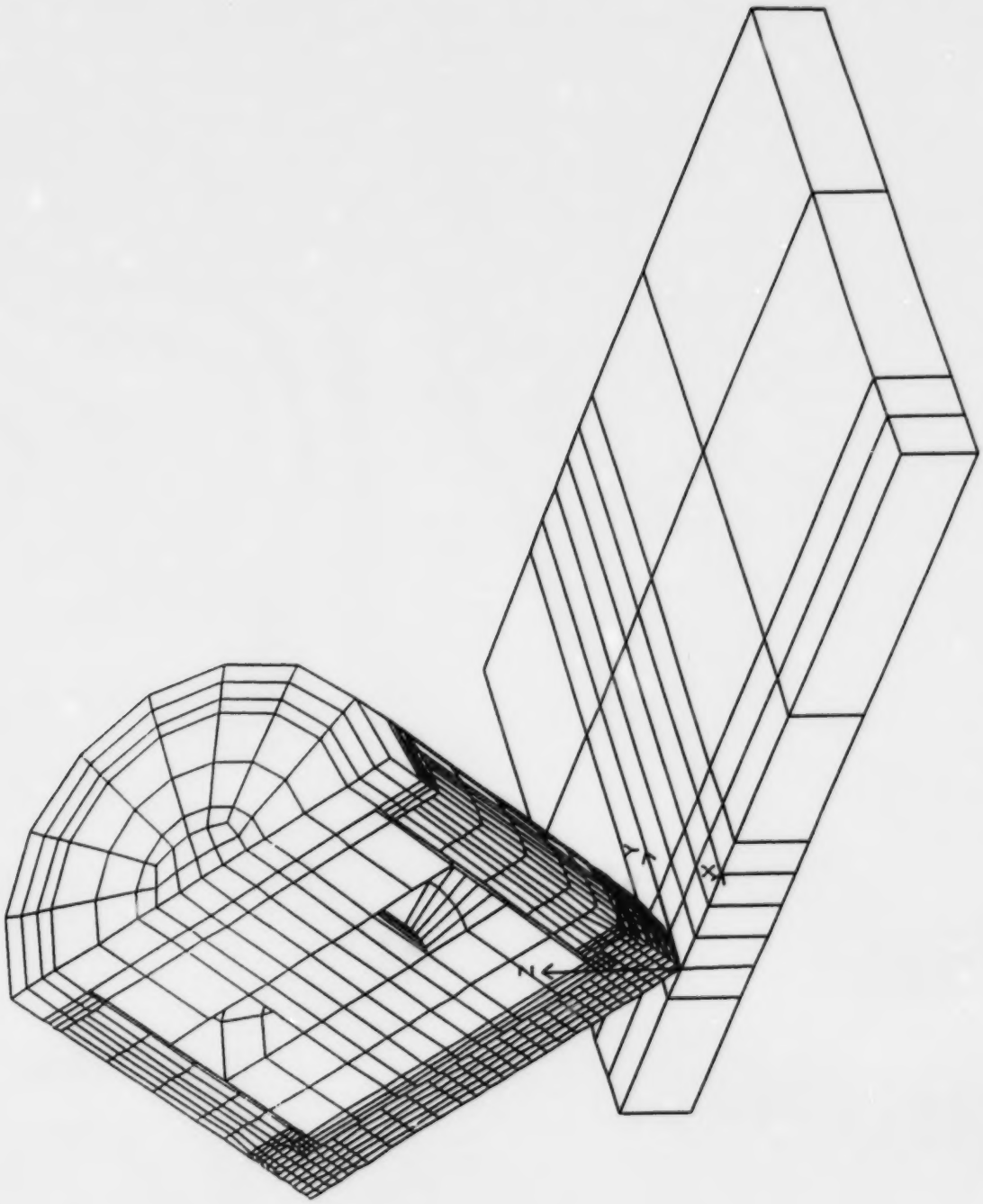


FIGURE 3.1.2
RFTP UNDEFORMED GEOMETRY (OBLIQUE VIEW)

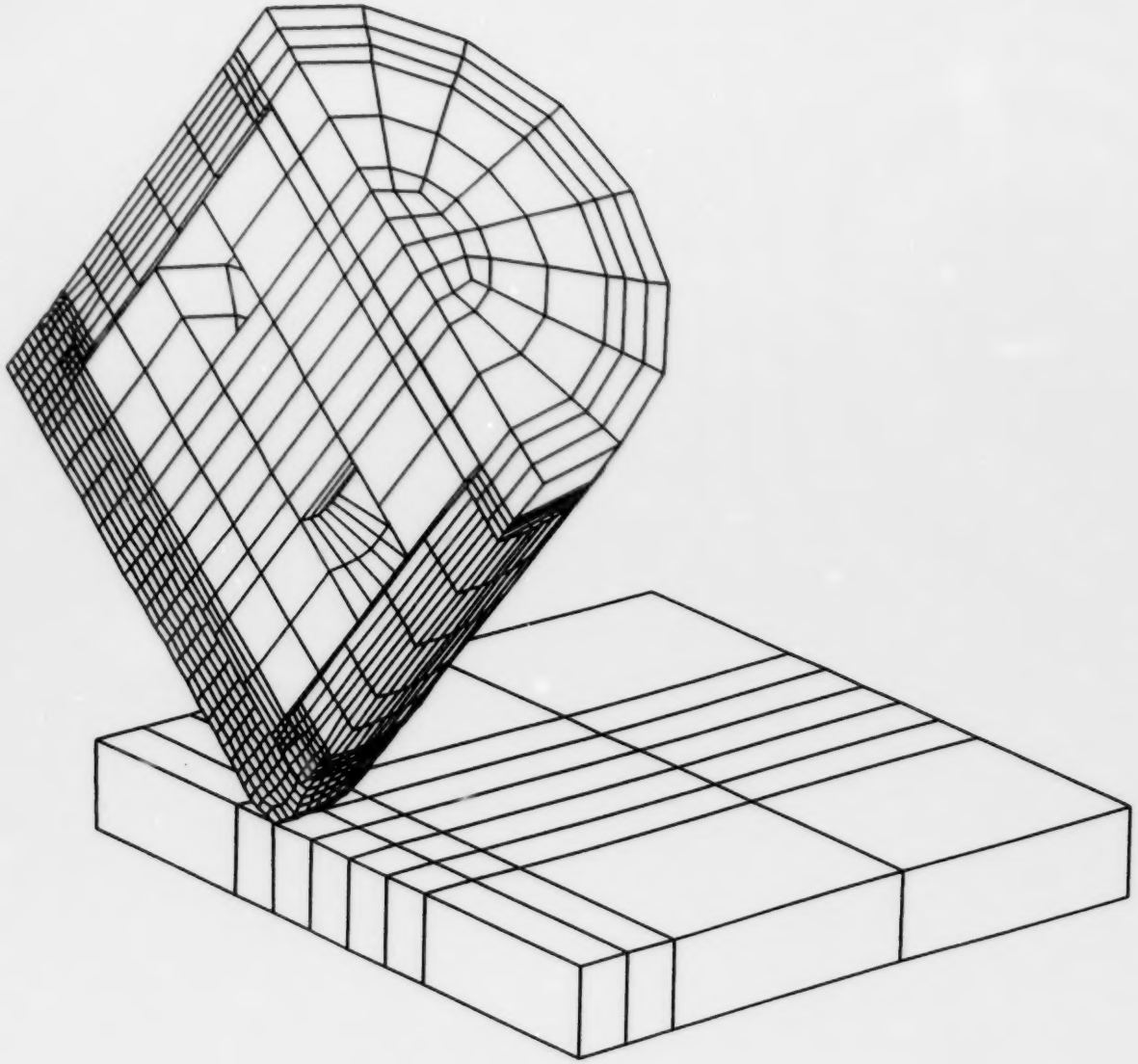


FIGURE 3.1.3
RFTP DEFORMED GEOMETRY (TIME = 1 ms)

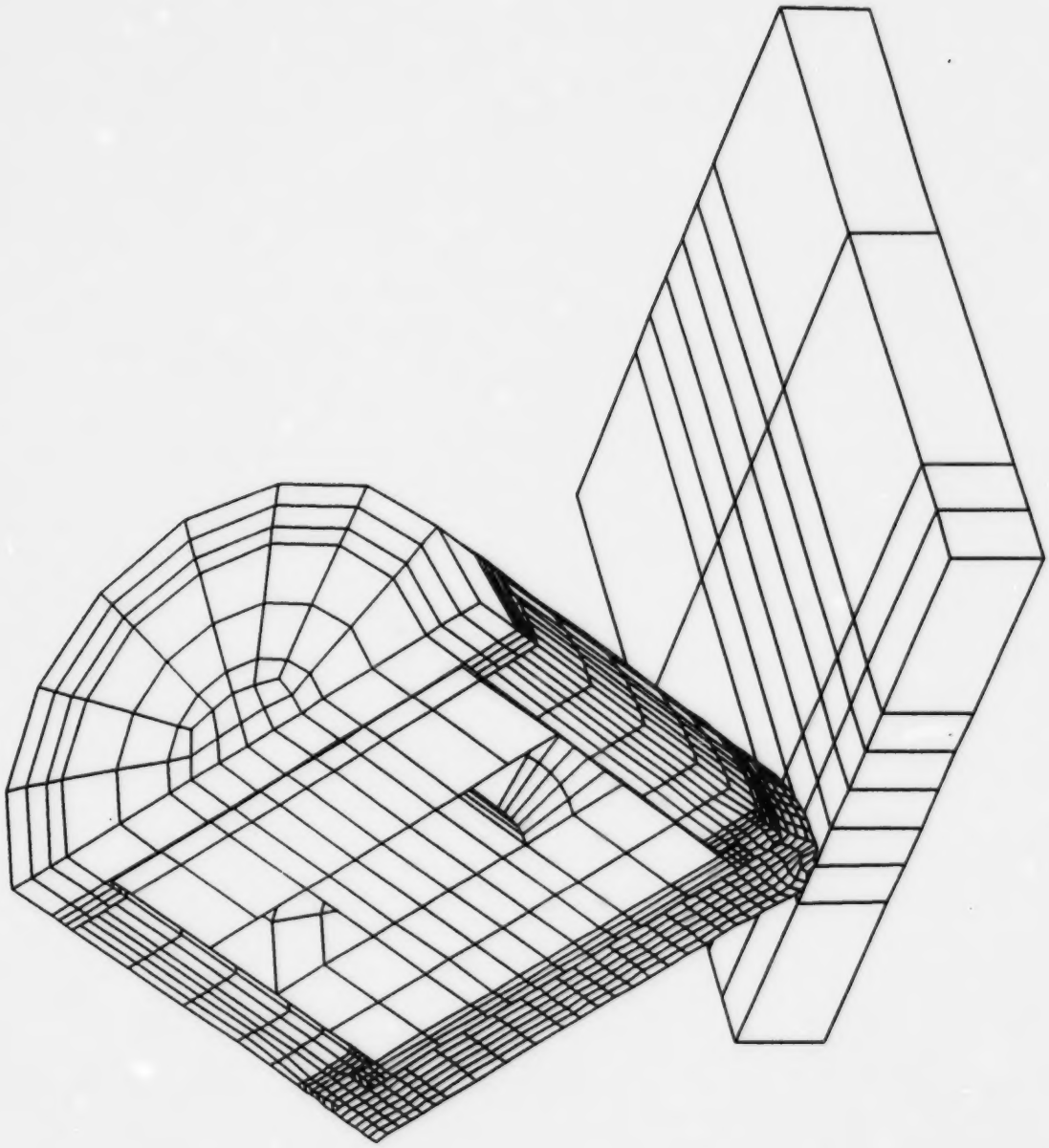


FIGURE 3.1.4
RFTP DEFORMED GEOMETRY (TIME = 2 ms)

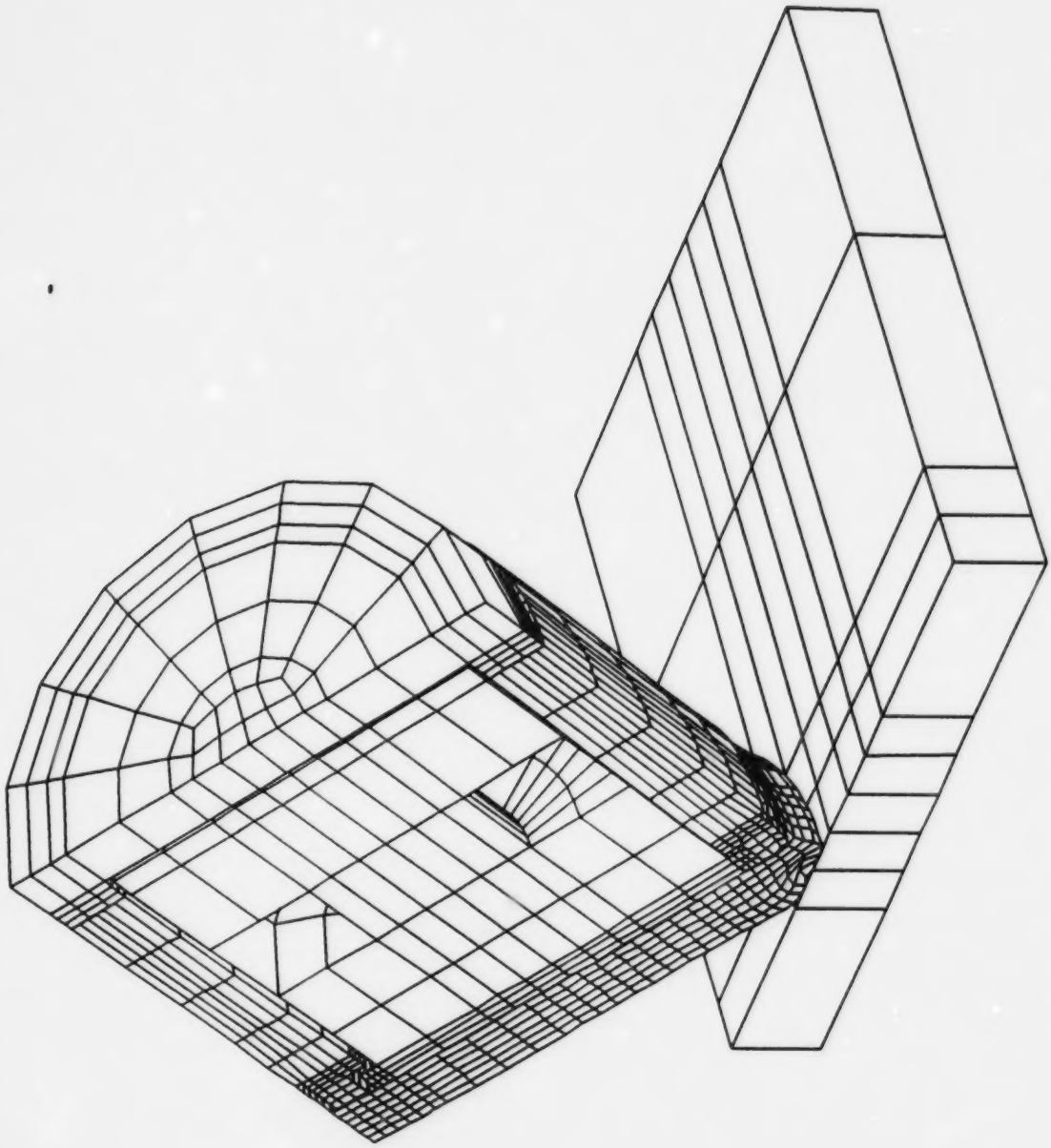


FIGURE 3.1.5
RFTP DEFORMED GEOMETRY (TIME = 3 ms)

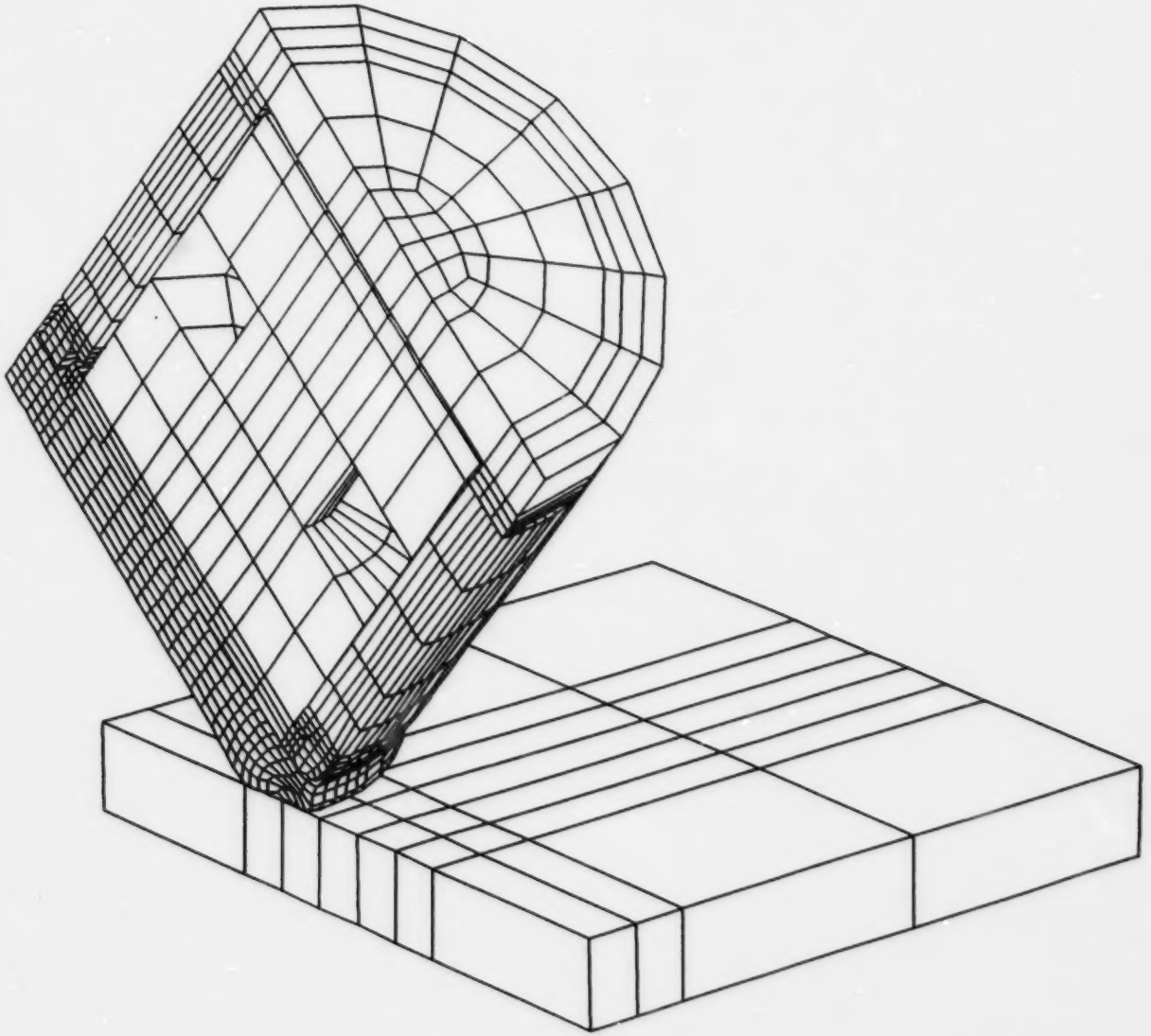


FIGURE 3.1.6
RFTP DEFORMED GEOMETRY (TIME = 4 ms)

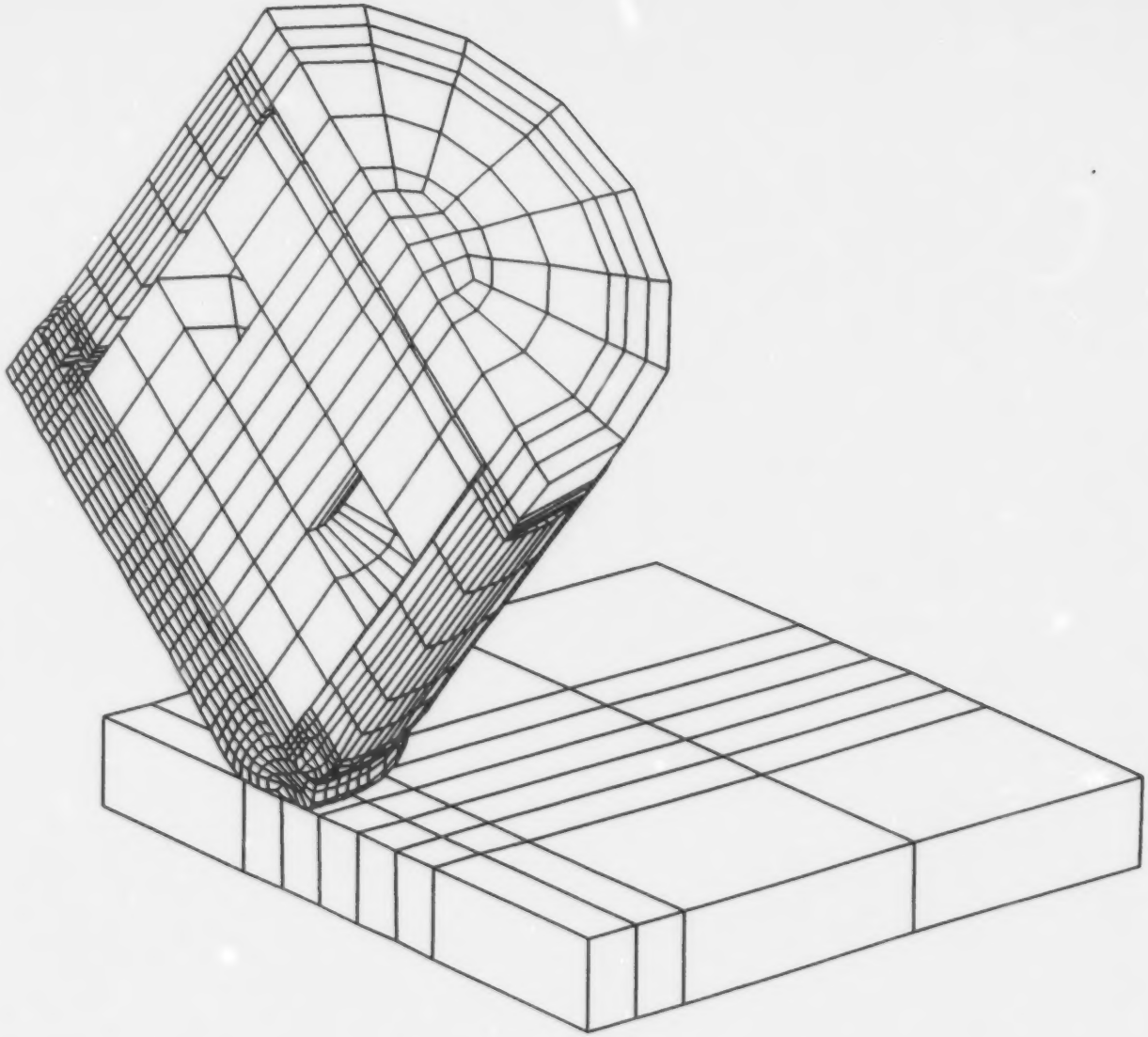


FIGURE 3.1.7
RFTP DEFORMED GEOMETRY (TIME = 5 ms)

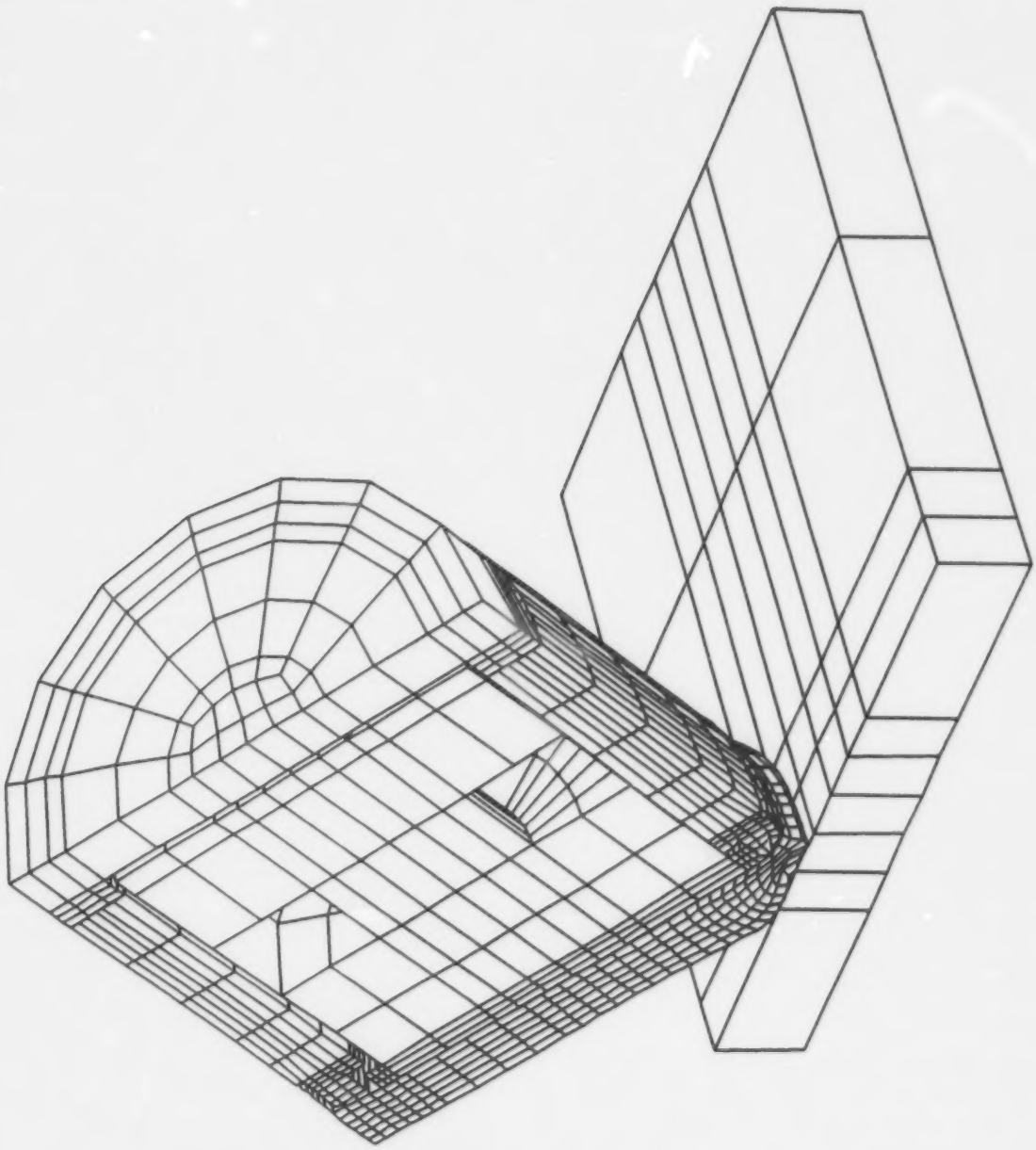


FIGURE 3.1.8
RFTP DEFORMED GEOMETRY (TIME = 6 ms)

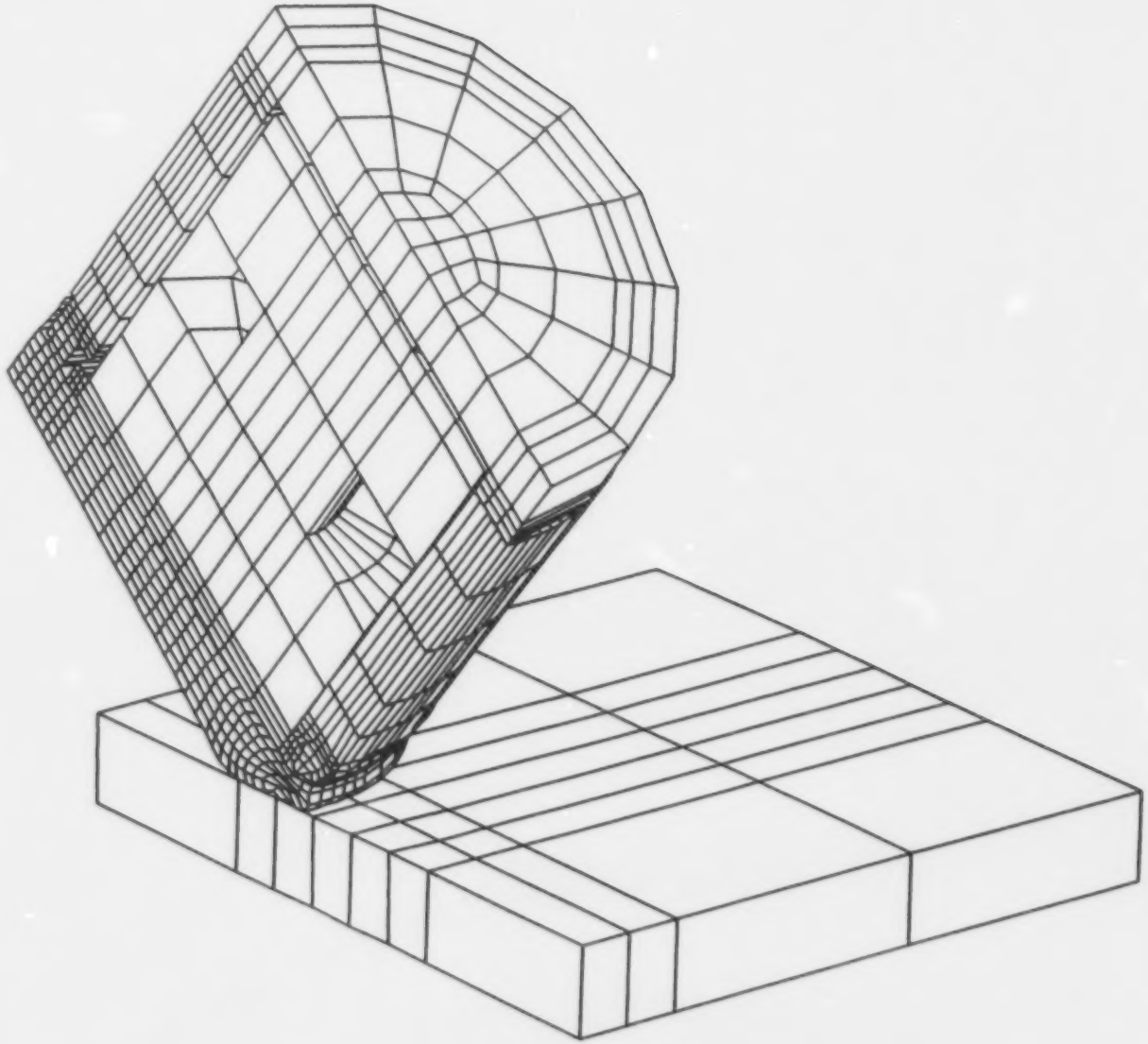


FIGURE 3.1.9
RFTP FINAL DEFORMED GEOMETRY (TIME = 7 ms)

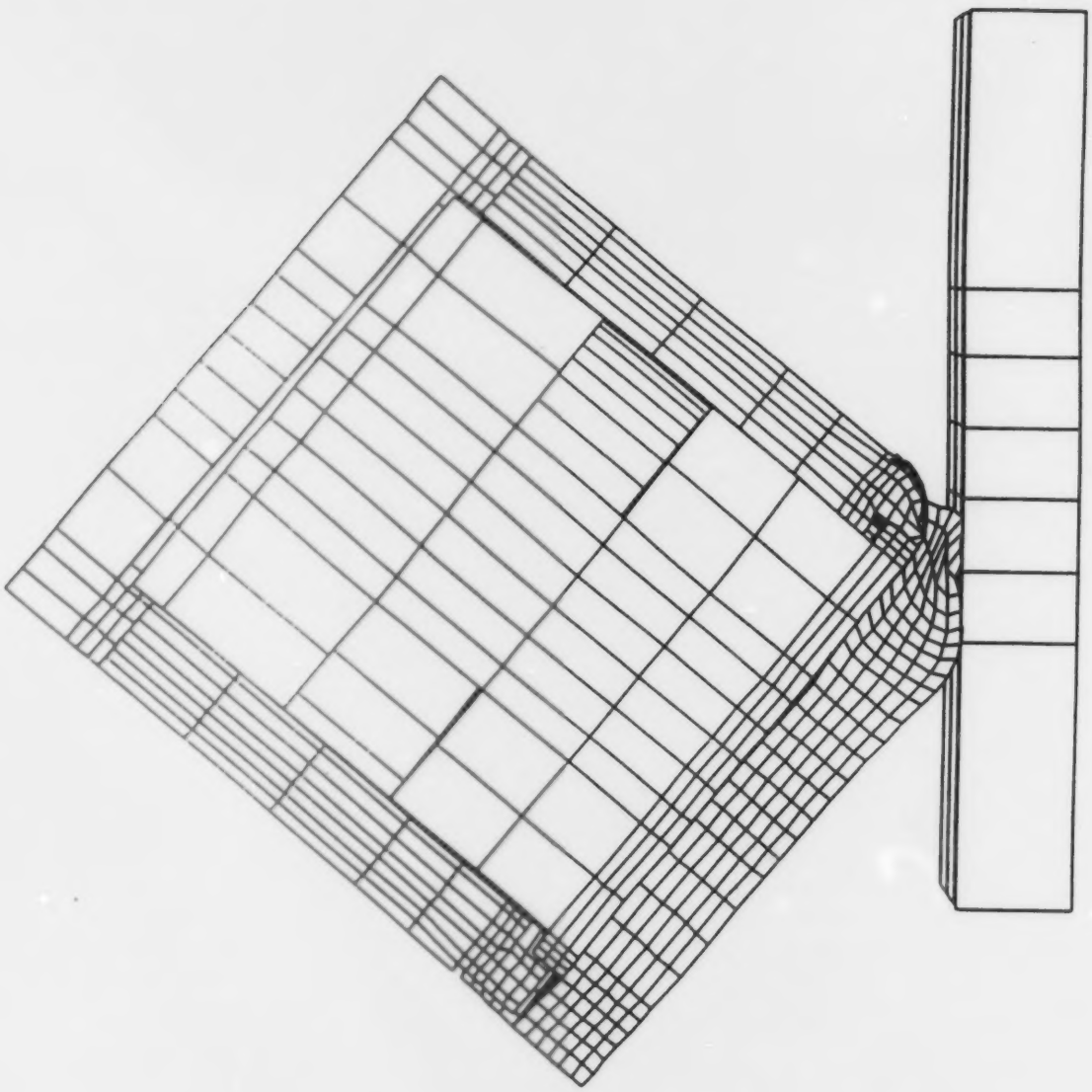


FIGURE 3.1.10
RFTP FINAL DEFORMED GEOMETRY (SIDE VIEW)

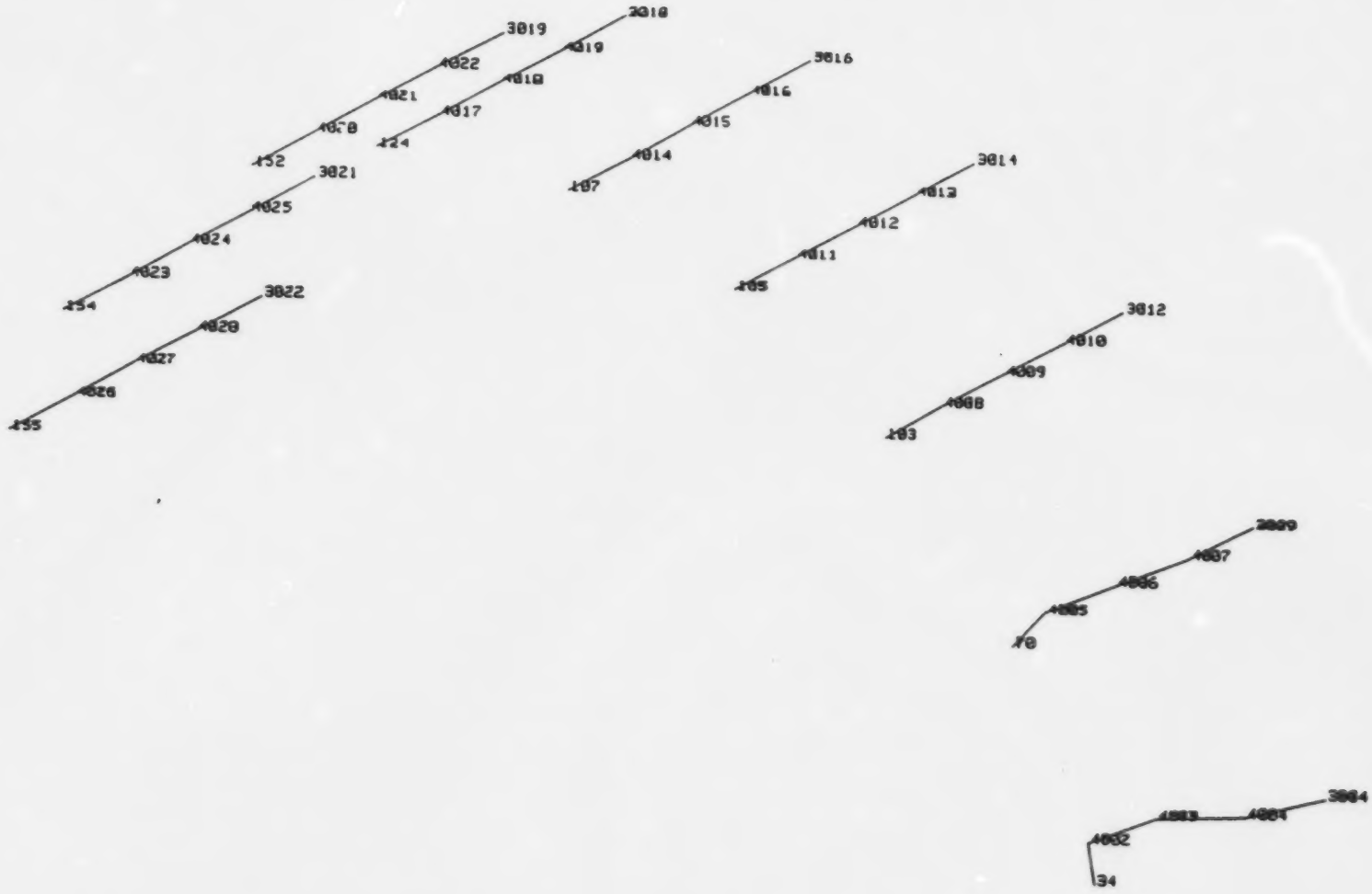


FIGURE 3.1.11
DEFORMED GEOMETRY OF OVERPACK LID BOLTS

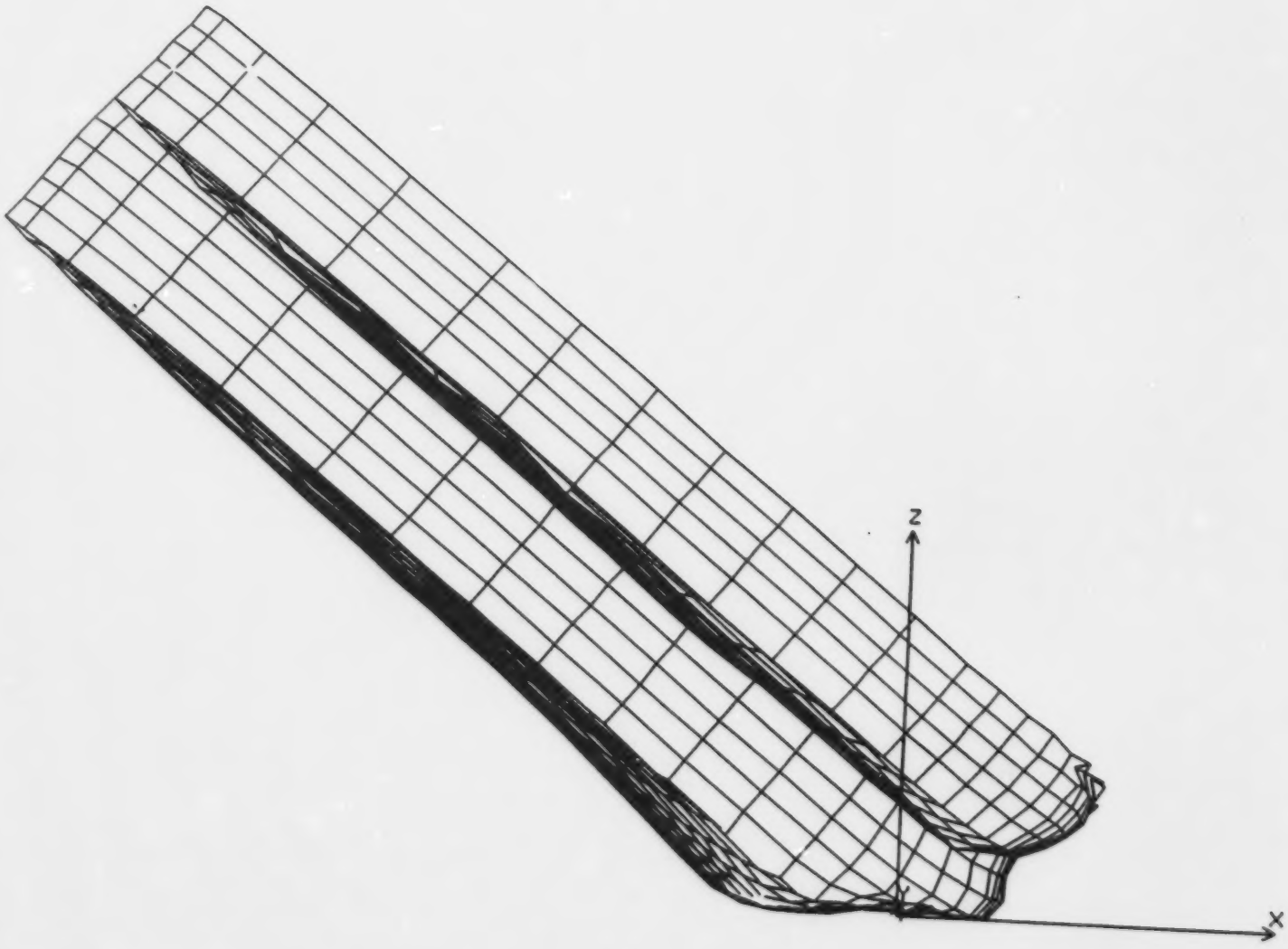


FIGURE 3.1.12
DEFORMED GEOMETRY OF OVERPACK SHELL ELEMENTS

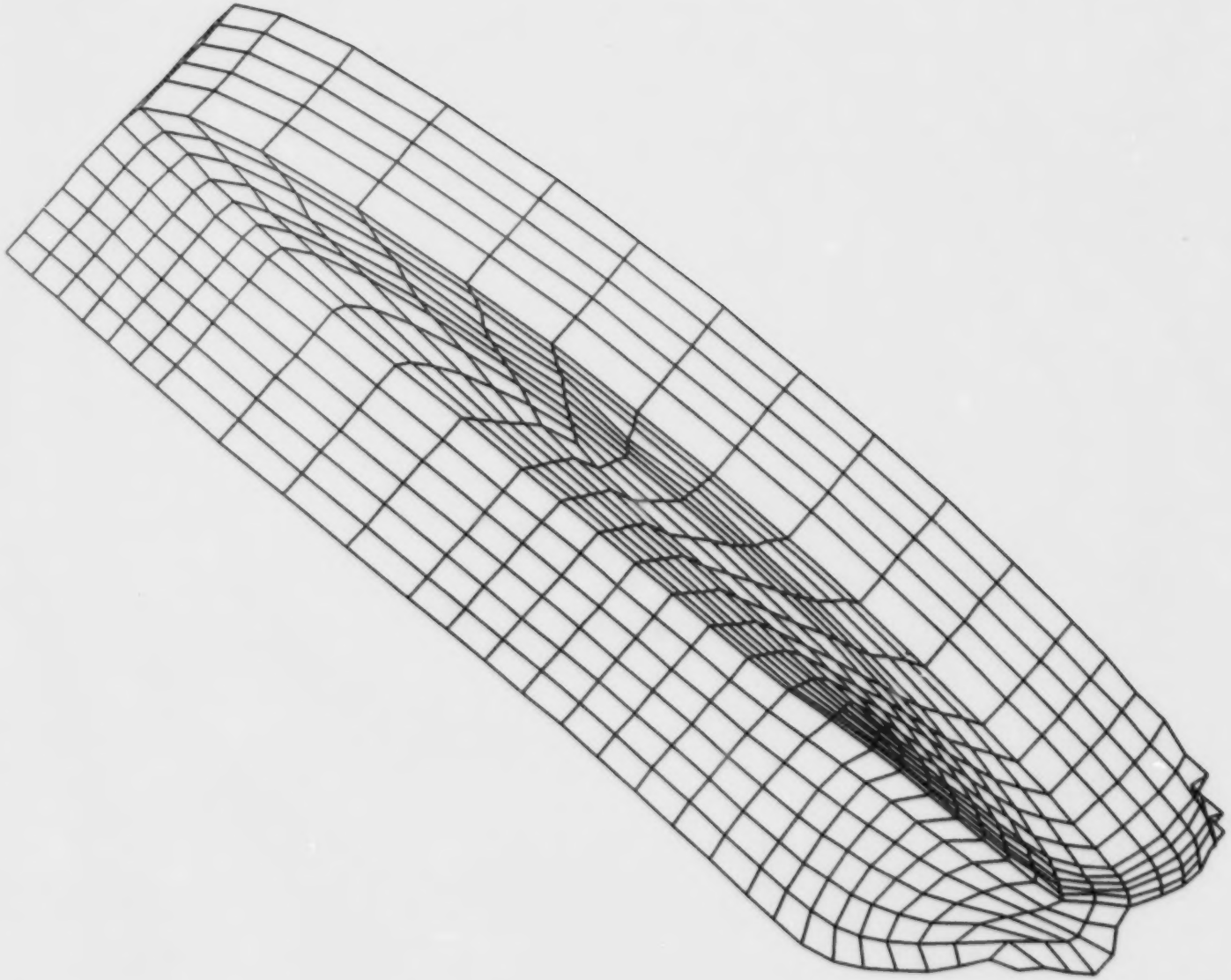


FIGURE 3.1.13
DEFORMED GEOMETRY OF OVERPACK LID

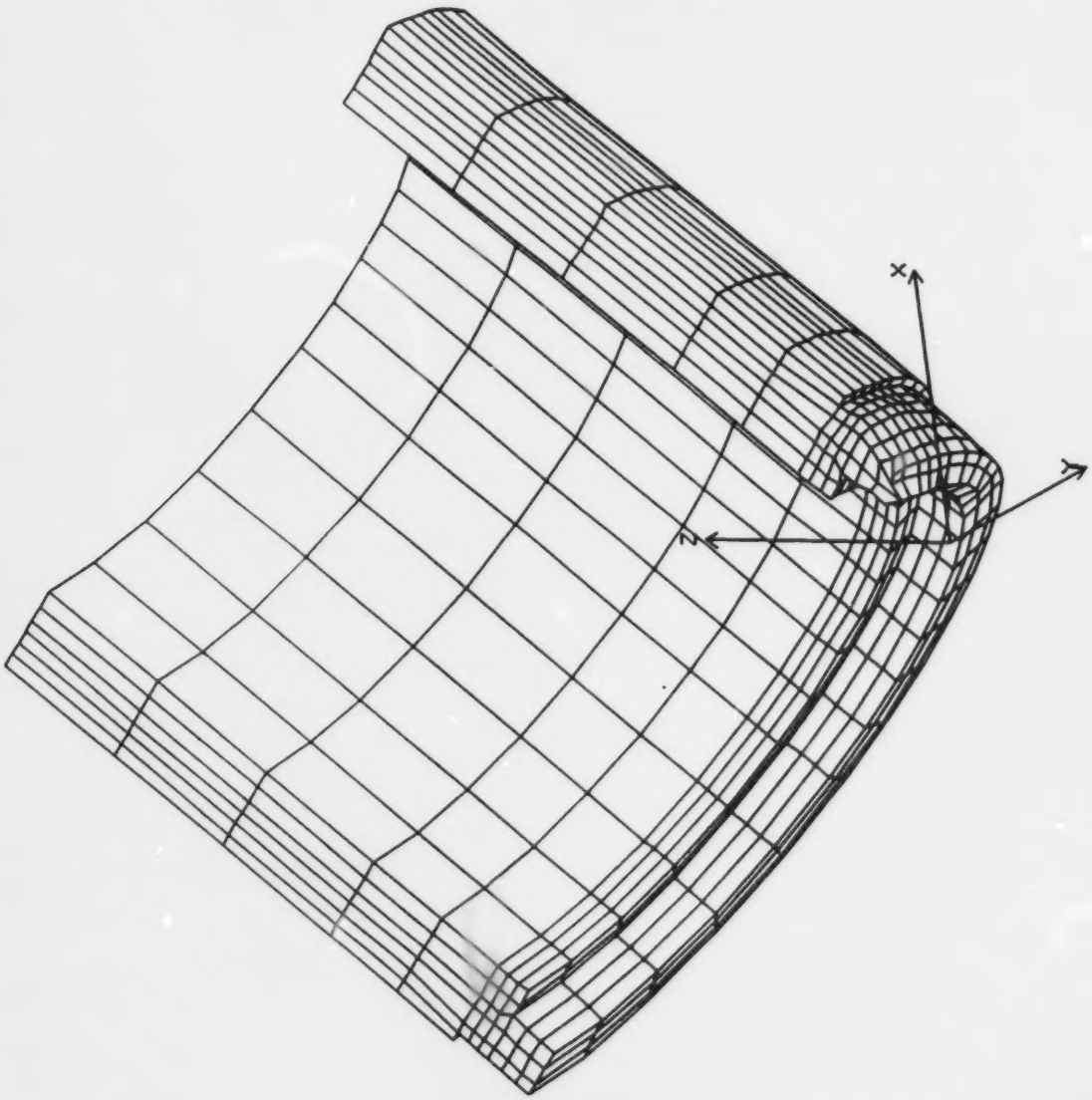
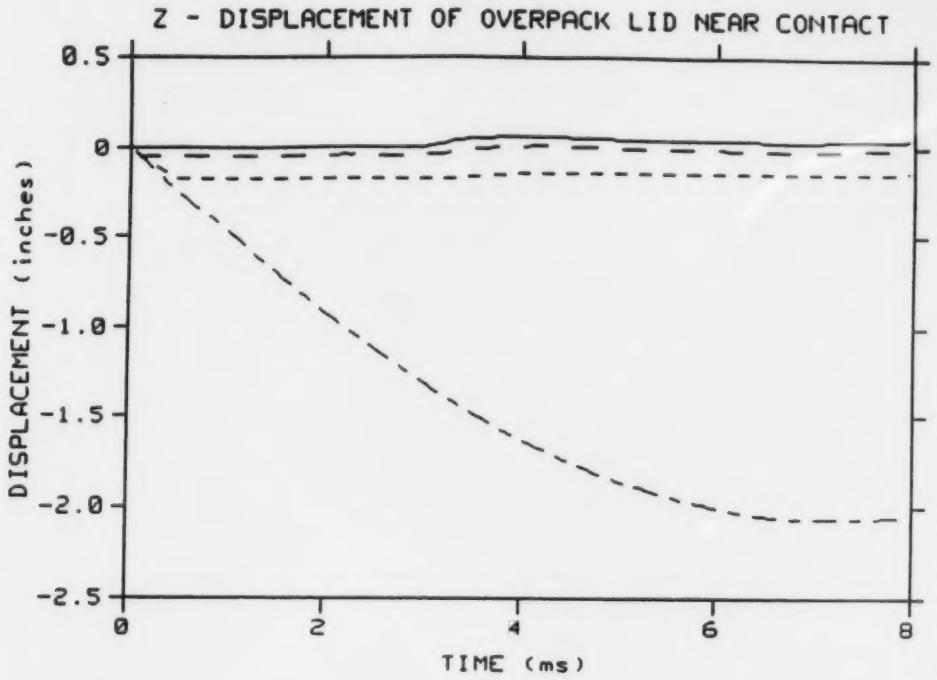


FIGURE 3.1.14
DEFORMED GEOMETRY OF OVERPACK BODY



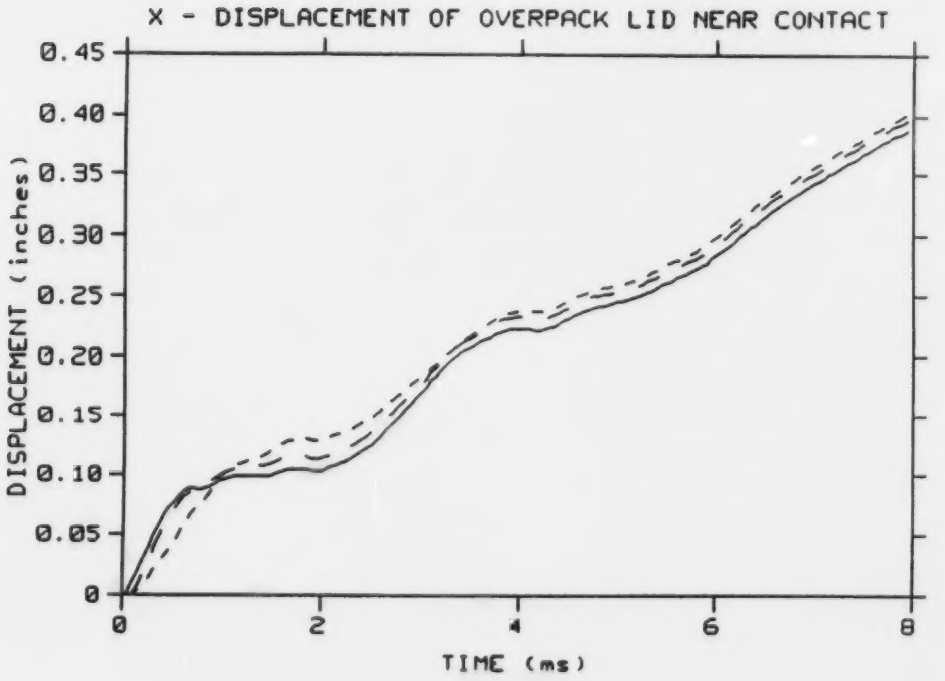
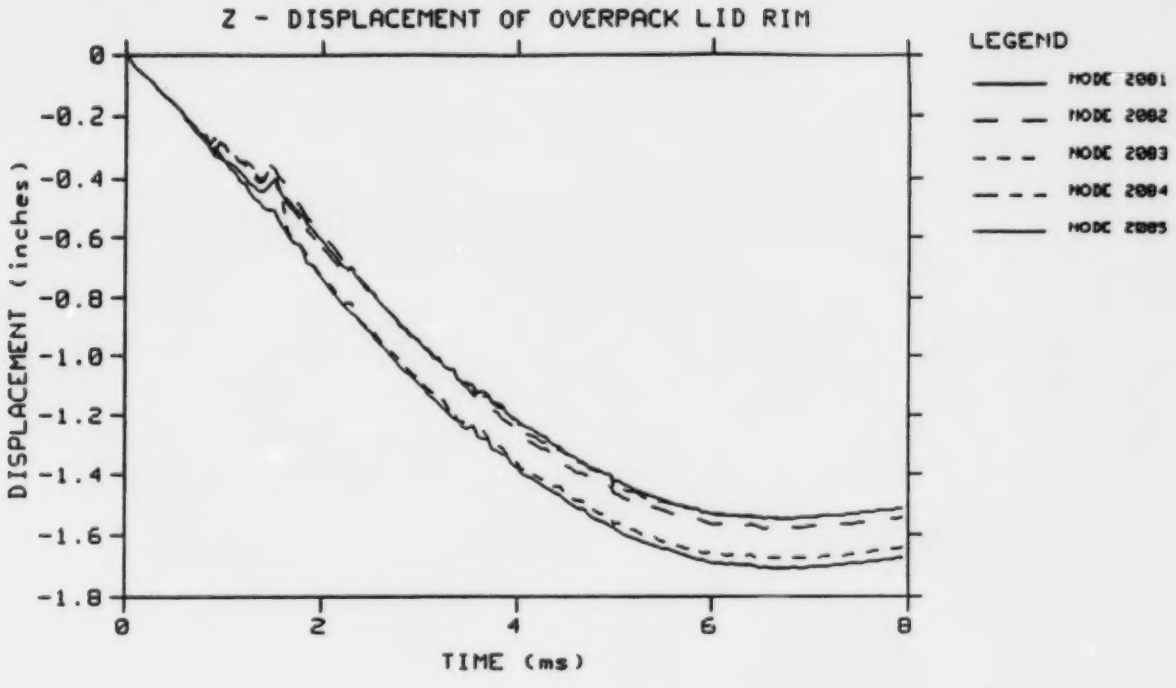


FIGURE 3.1.15
DISPLACEMENT TIME HISTORY OF NODES ON EDGE
OF OVERPACK LID



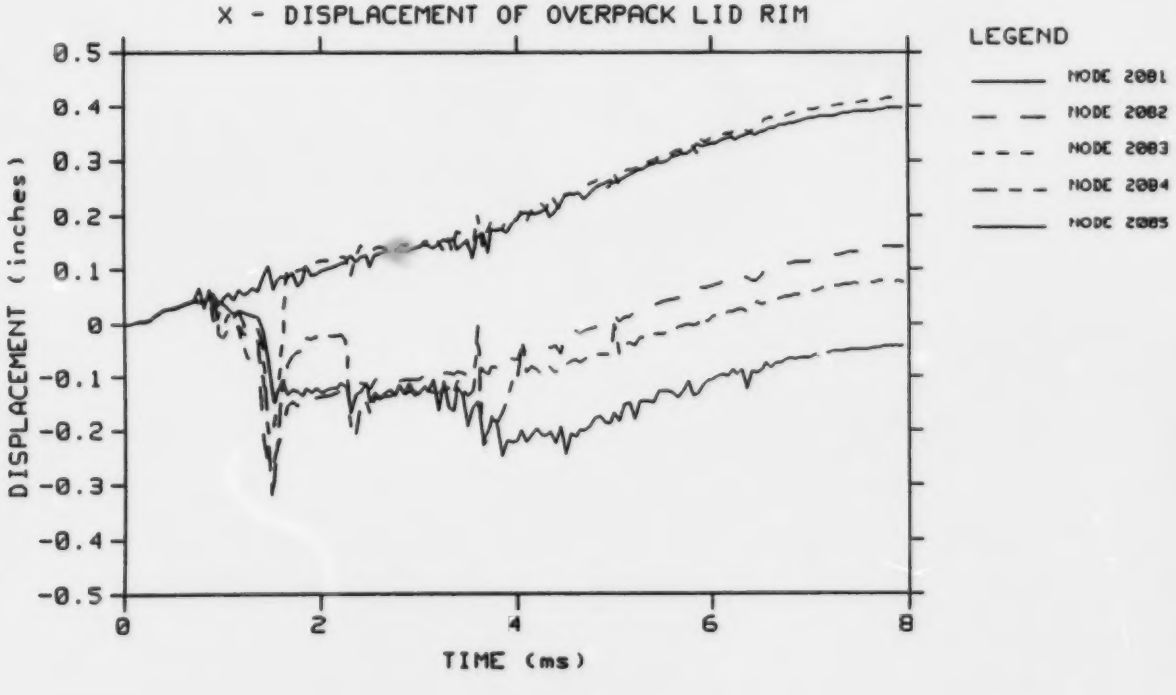
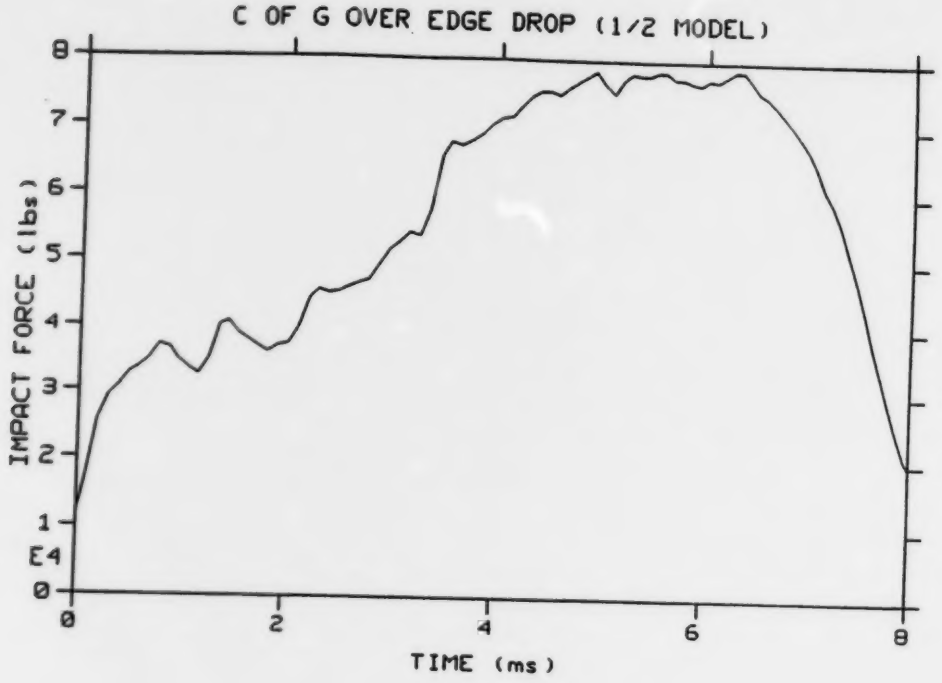
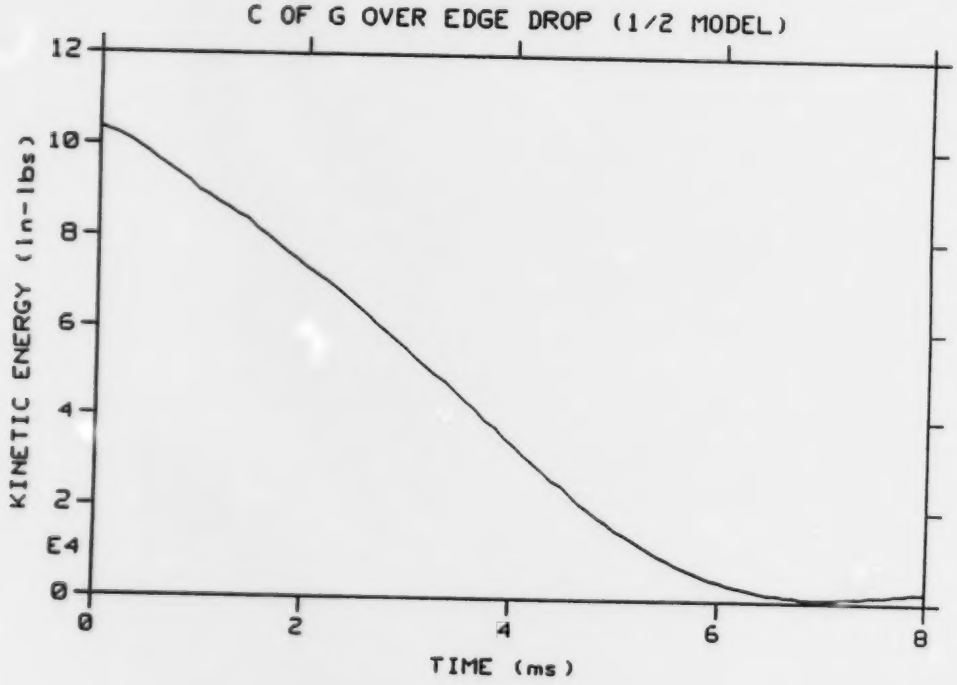


FIGURE 3.1.16
DISPLACEMENT TIME HISTORY OF NODES ON RIM OF OVERPACK LID

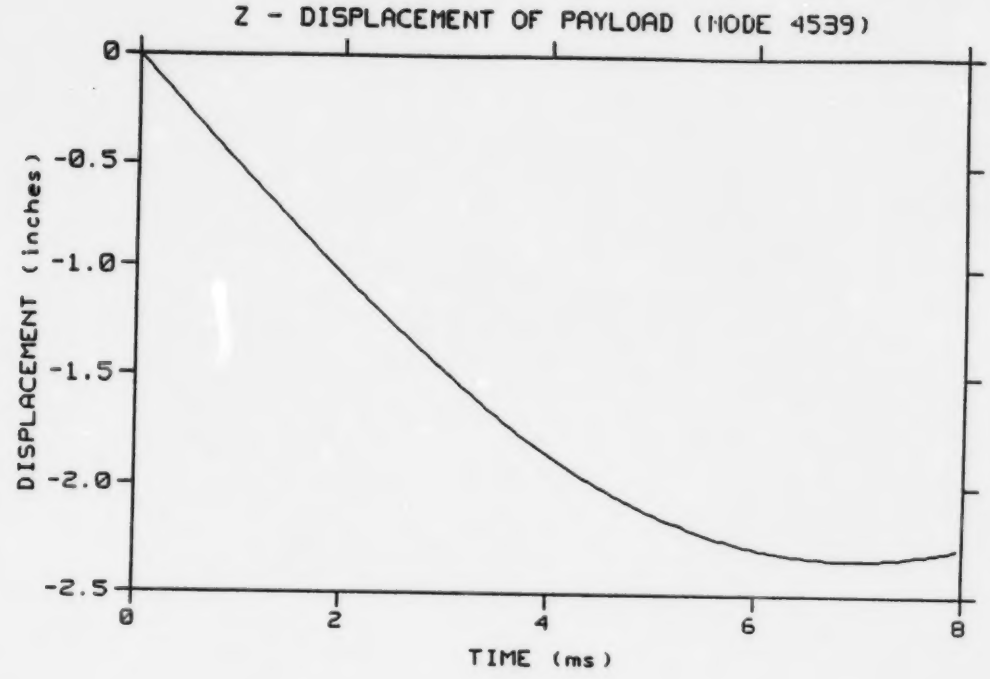


(a)



(b)

FIGURE 3.1.17
TIME HISTORY OF IMPACT FORCE AND
KINETIC ENERGY



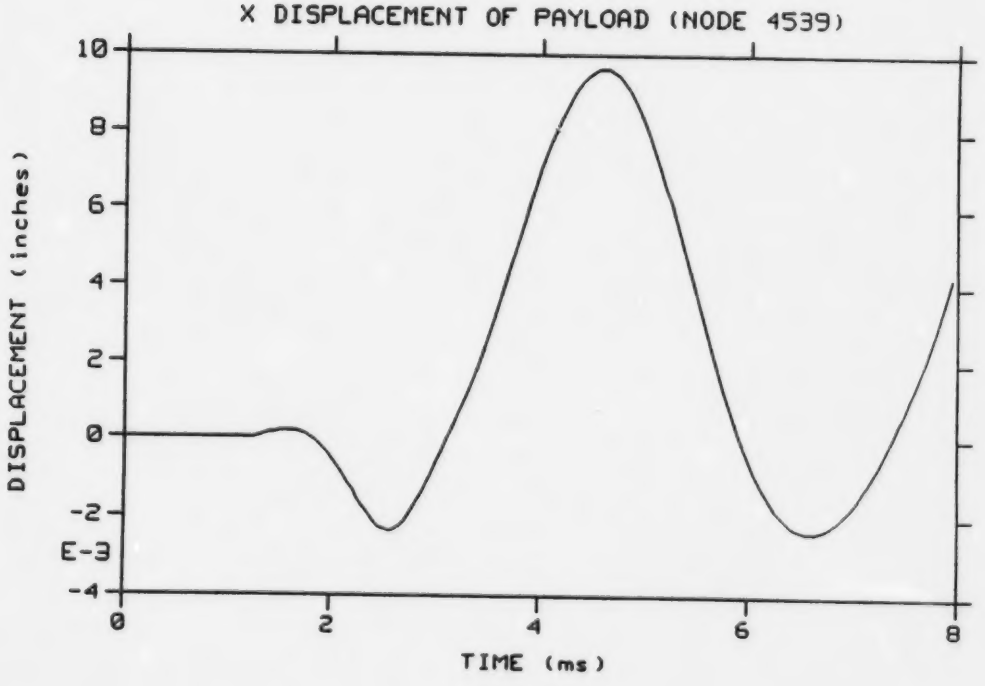
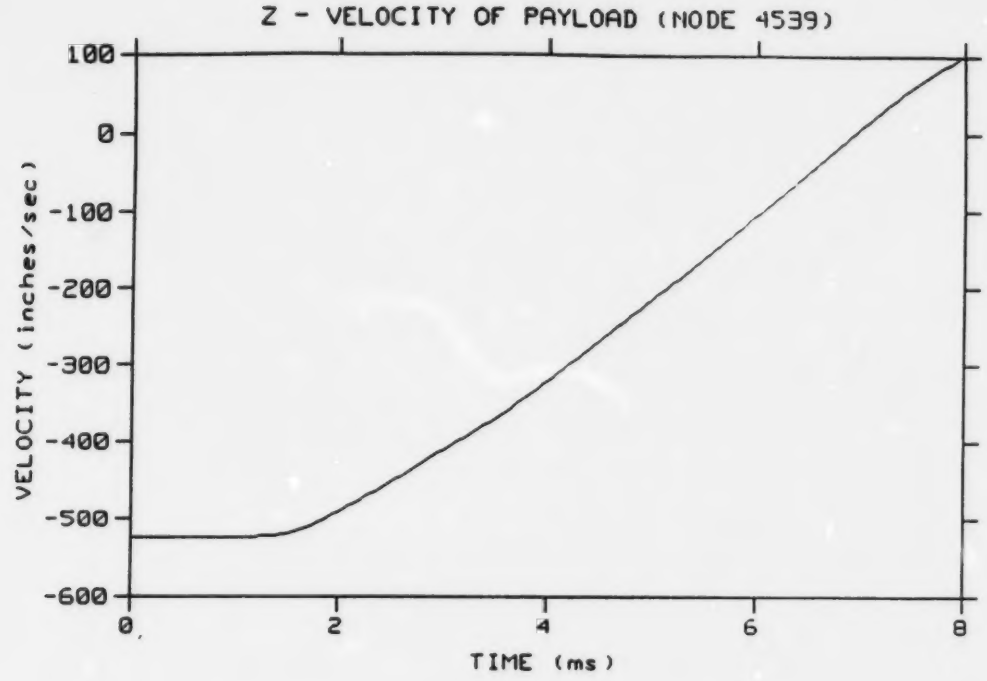


FIGURE 3.1.18
DISPLACEMENT TIME HISTORY OF PAYLOAD



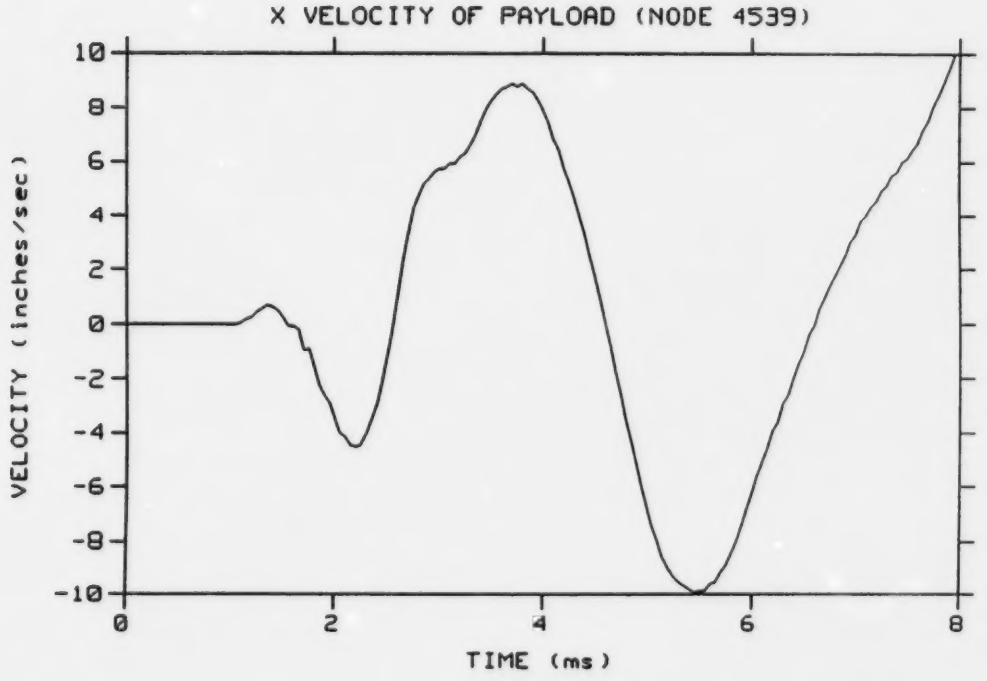
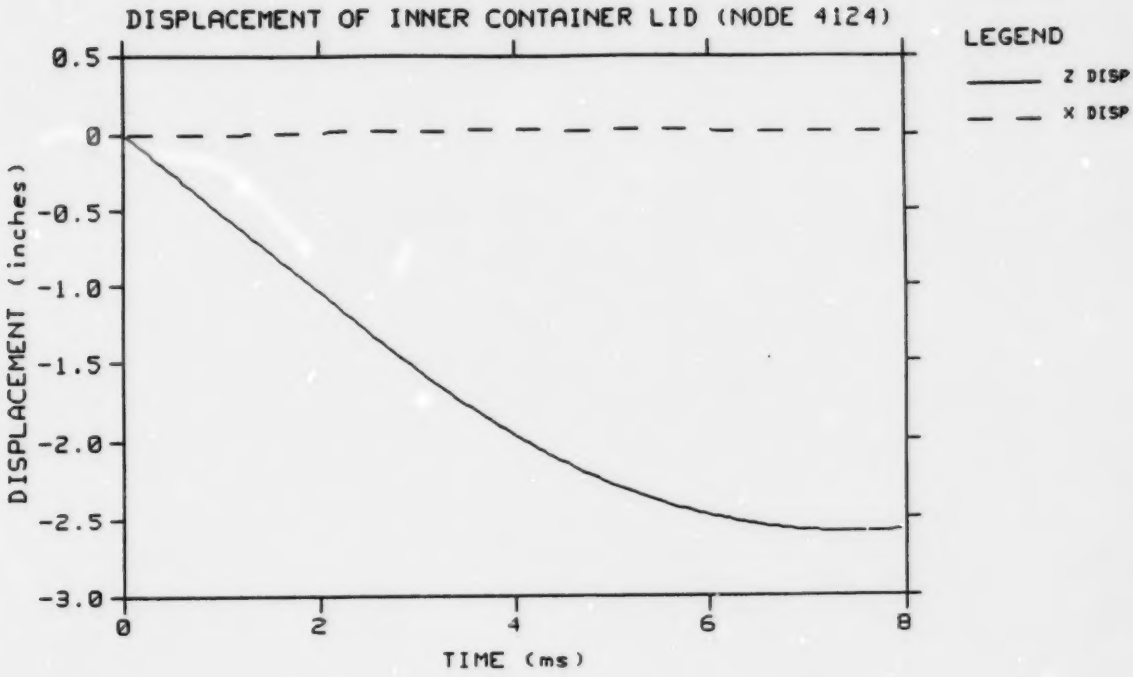


FIGURE 3.1.19
VELOCITY TIME HISTORY OF PAYLOAD



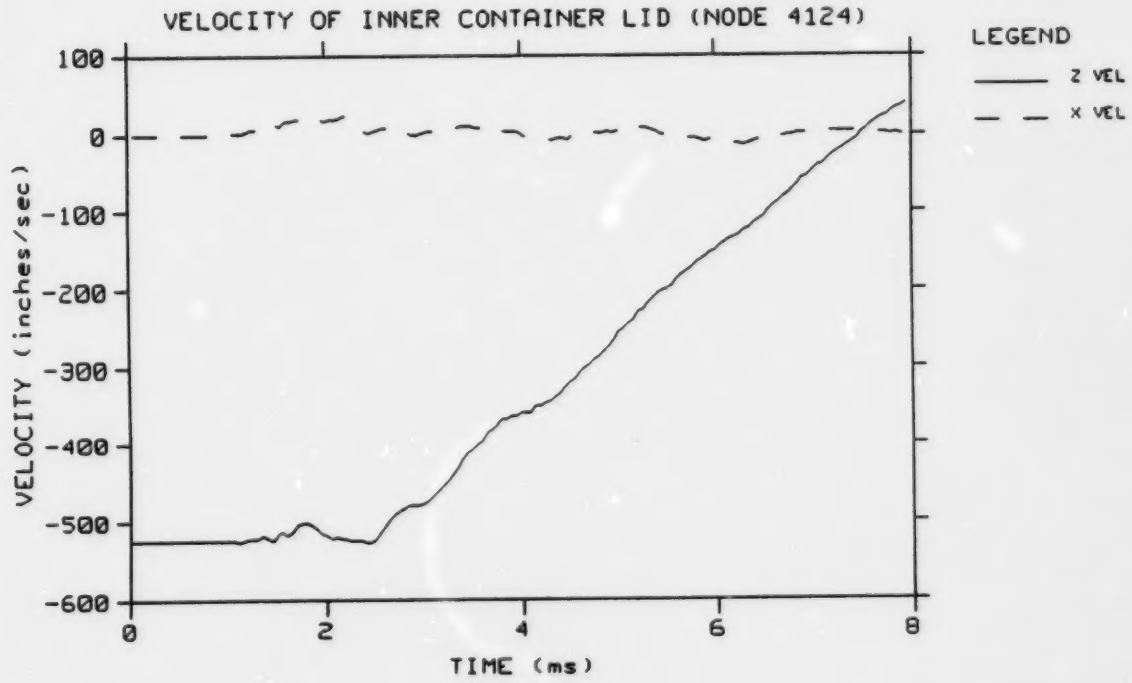
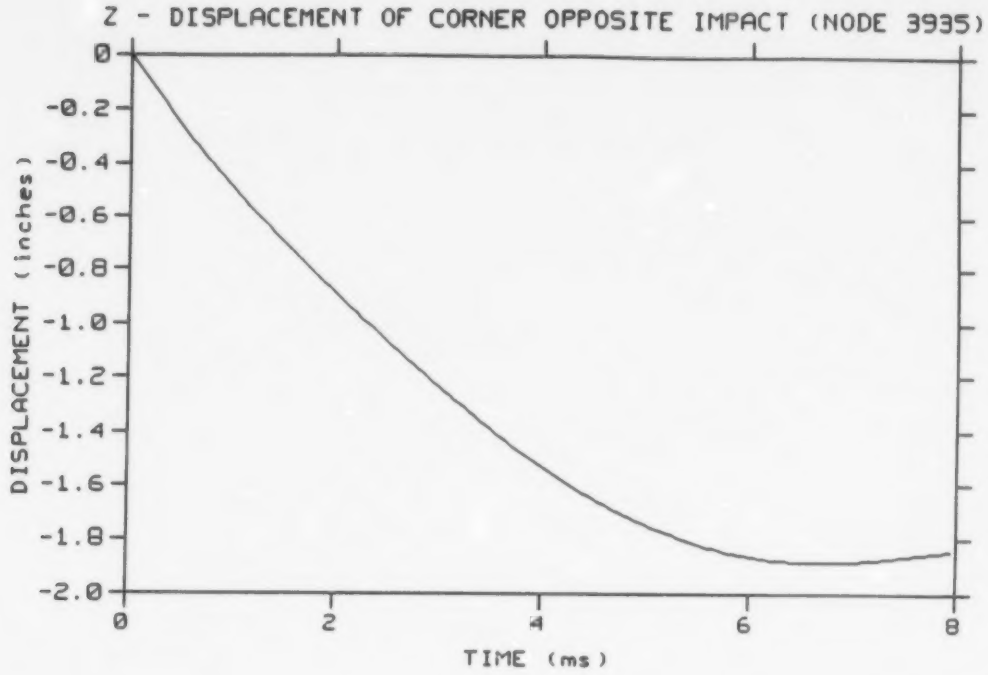


FIGURE 3.1.20
DISPLACEMENT AND VELOCITY TIME HISTORY OF
INNER CONTAINER LID



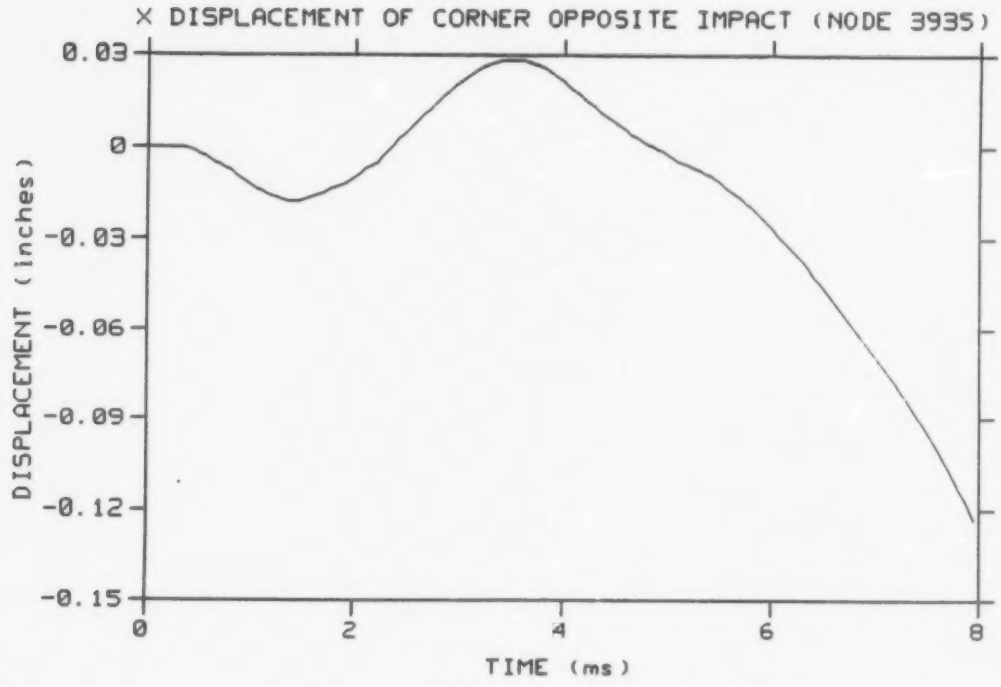
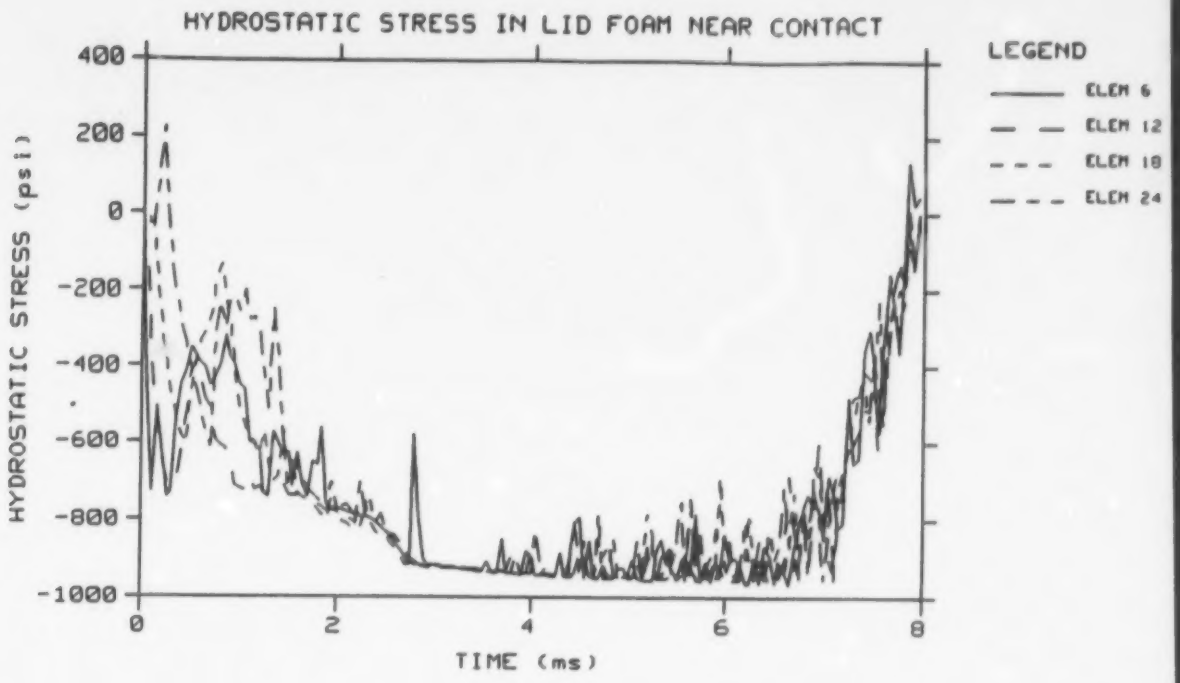
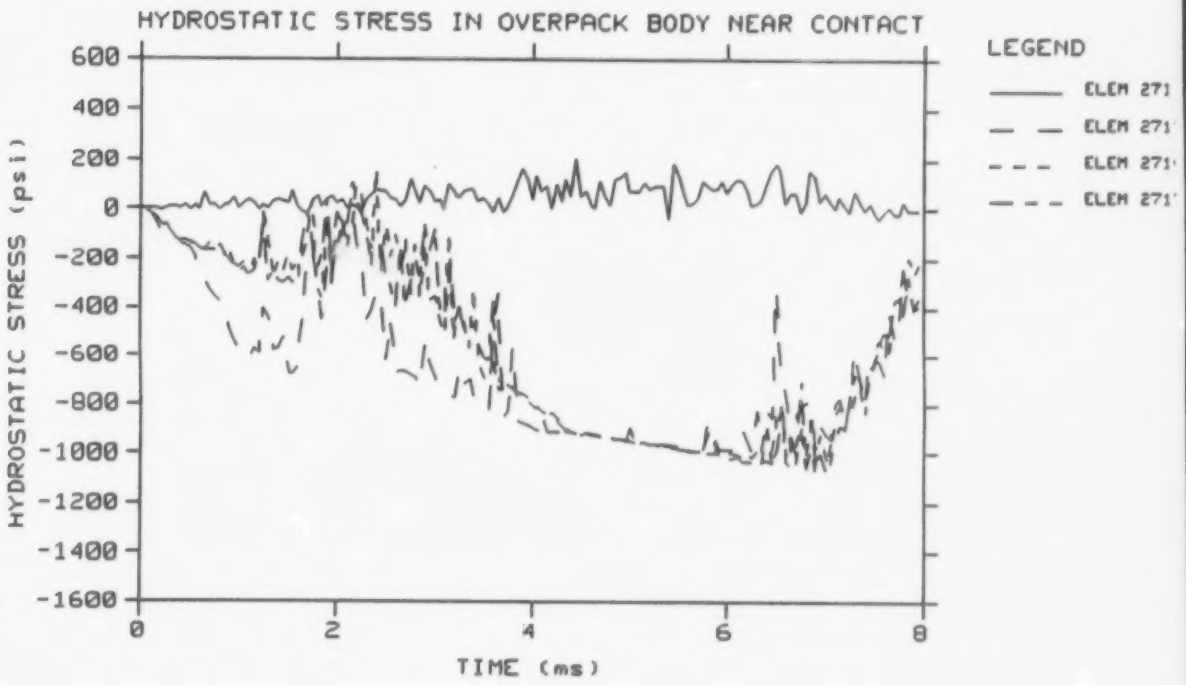


FIGURE 3.1.21
DISPLACEMENT TIME HISTORY OF
CORNER OPPOSITE IMPACT



(a)



(b)

FIGURE 3.1.22
HYDROSTATIC STRESS TIME HISTORY IN
OVERPACK LID AND BODY FOAM

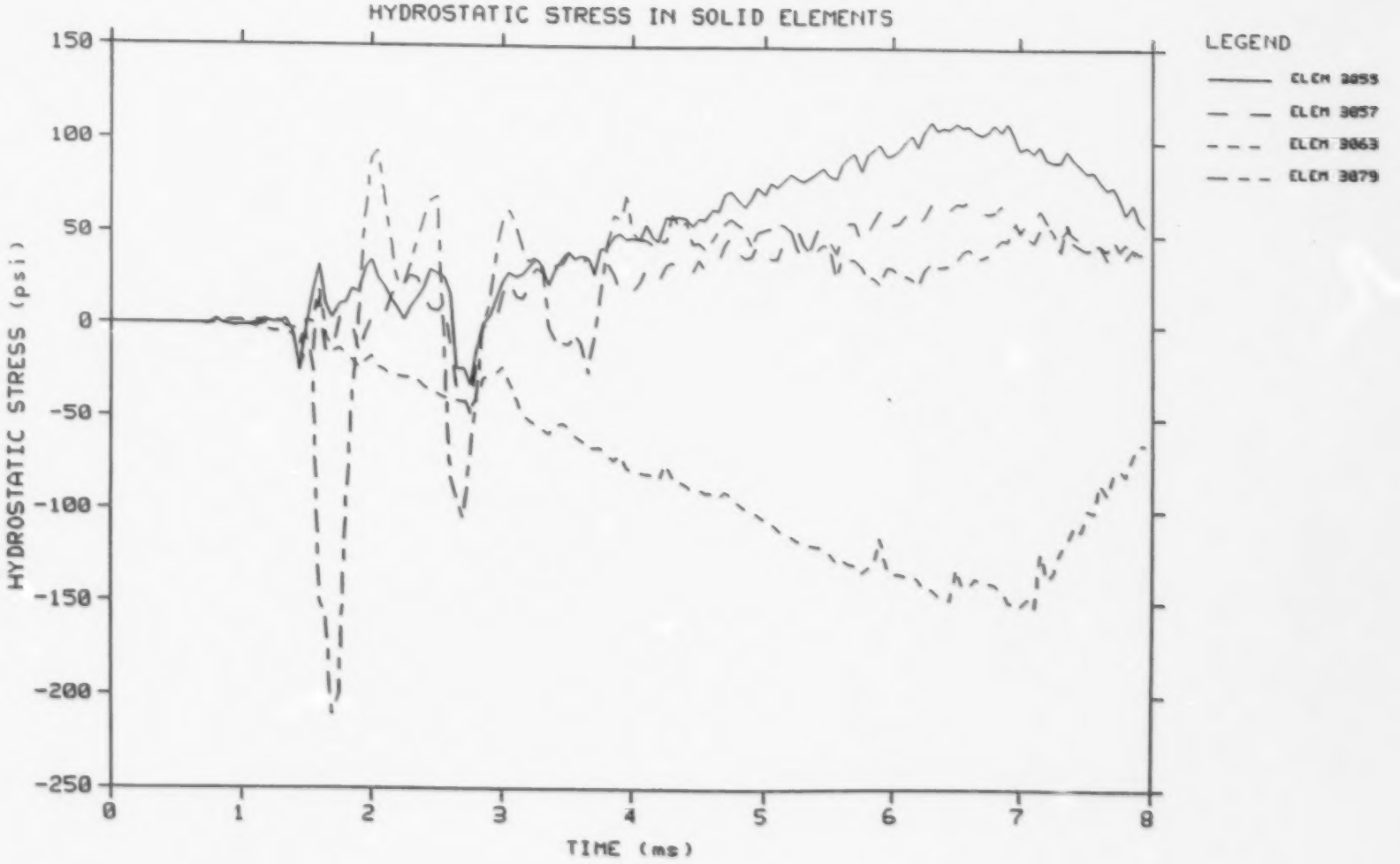
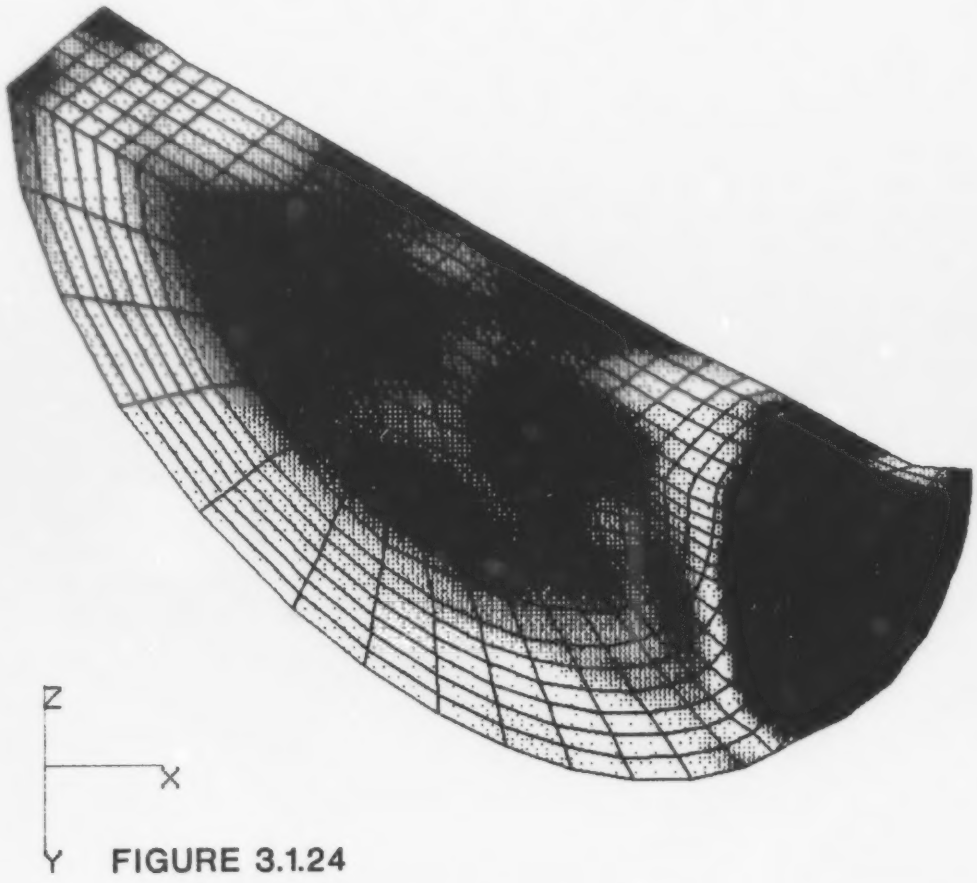


FIGURE 3.1.23
HYDROSTATIC STRESS TIME HISTORY IN
FOAM DUNNAGE BELOW PAYLOAD



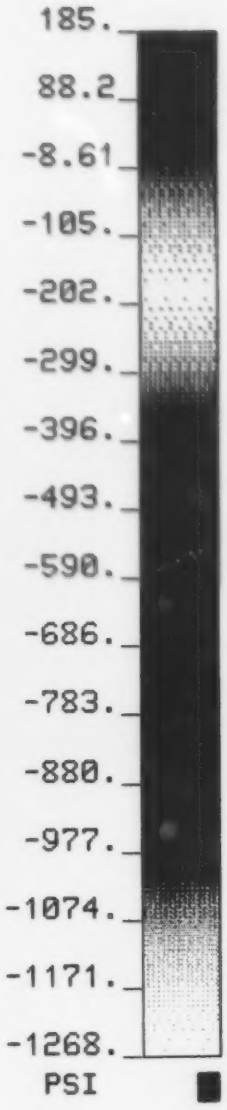


FIGURE 3.1.24

RFTP C OF G OVER EDGE 9m DROP
HYDROSTATIC STRESS AT TIME = 6 ms

T-06

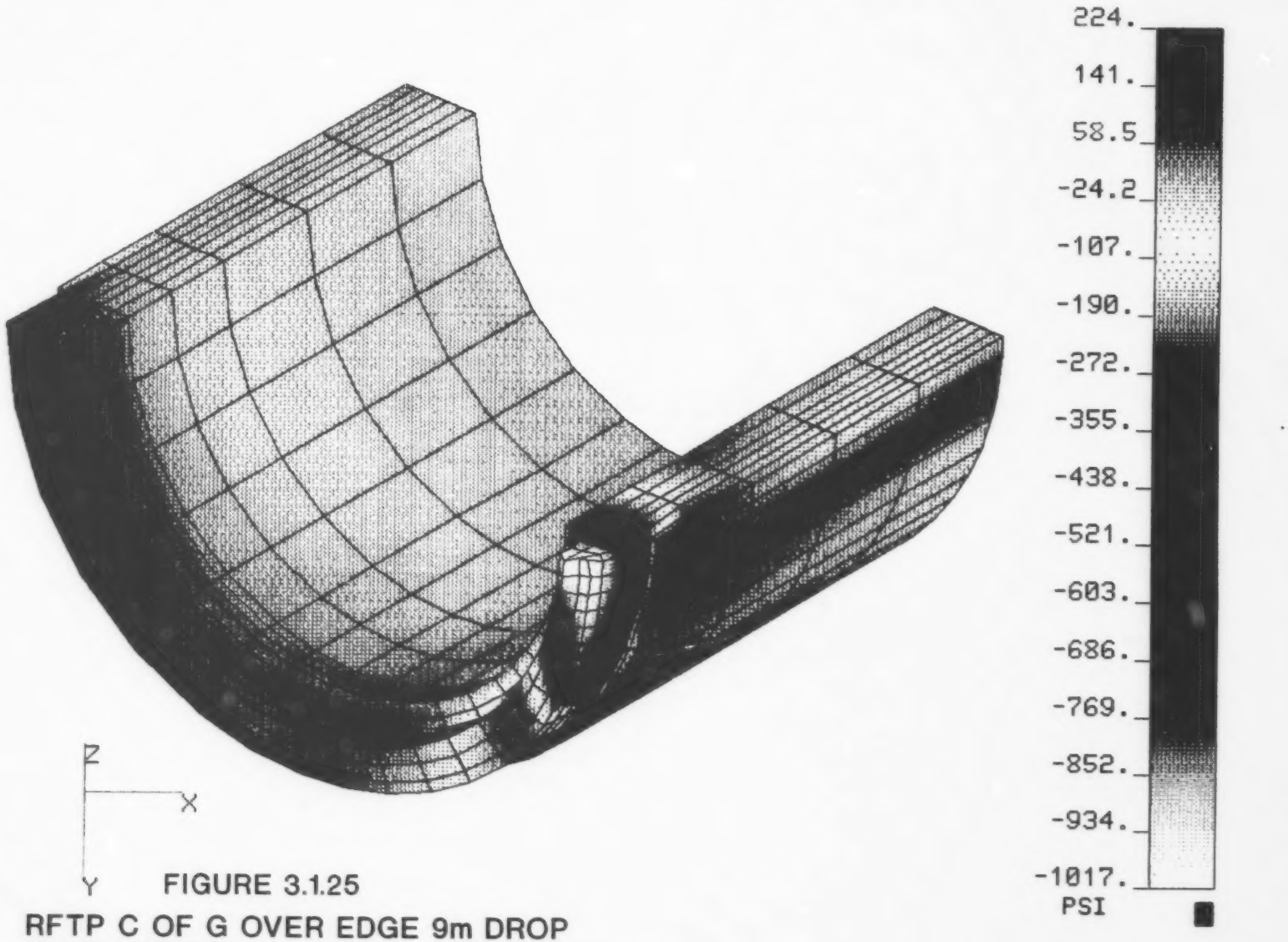


FIGURE 3.1.25

RFTP C OF G OVER EDGE 9m DROP
HYDROSTATIC STRESS AT TIME = 6 ms

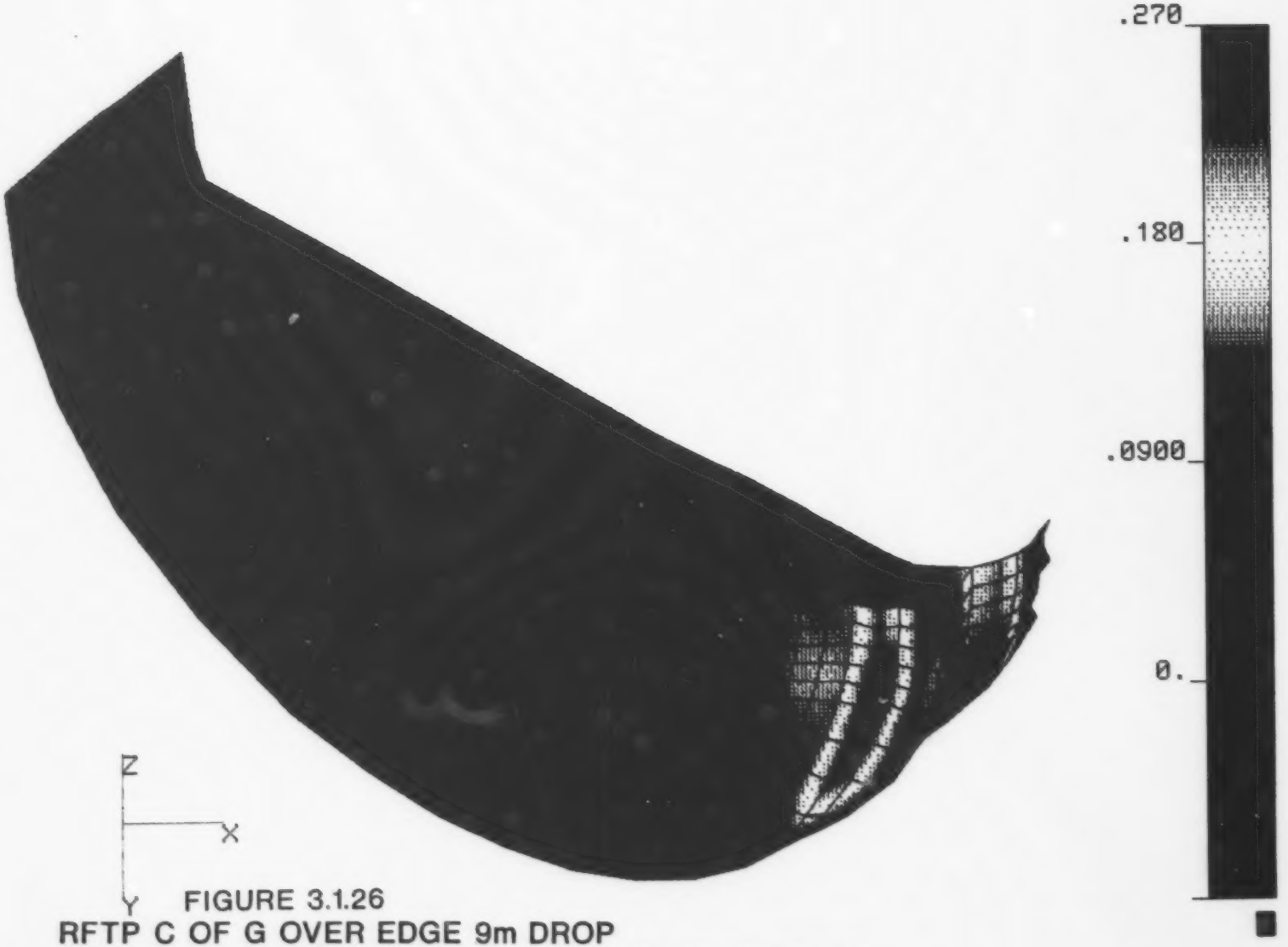


FIGURE 3.1.26
RFTP C OF G OVER EDGE 9m DROP
EFFECTIVE PLASTIC STRAIN ON OUTSIDE SURFACE

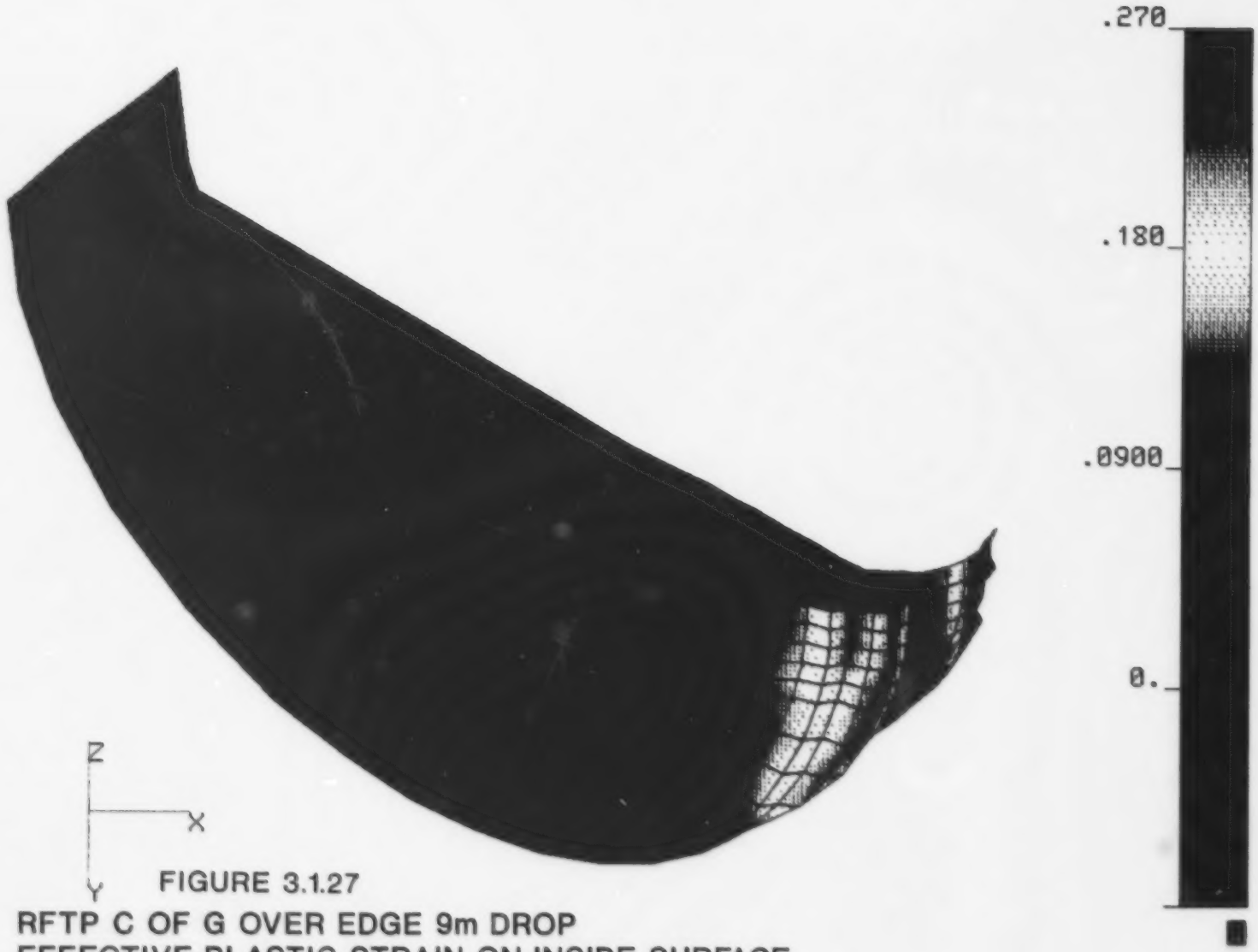


FIGURE 3.1.27
RFTP C OF G OVER EDGE 9m DROP
EFFECTIVE PLASTIC STRAIN ON INSIDE SURFACE

FIGURE 3.1.28

RFTP C OF G OVER EDGE 9m DROP
EFFECTIVE PLASTIC STRAIN ON OUTSIDE SURFACE

FIGURE 3.1.29
RFTP C OF G OVER EDGE 9m DROP
EFFECTIVE PLASTIC STRAIN ON INSIDE SURFACE

FIGURE 3.1.30

RFTP C OF G OVER EDGE 9m DROP
EFFECTIVE PLASTIC STRAIN ON OUTSIDE SURFACE

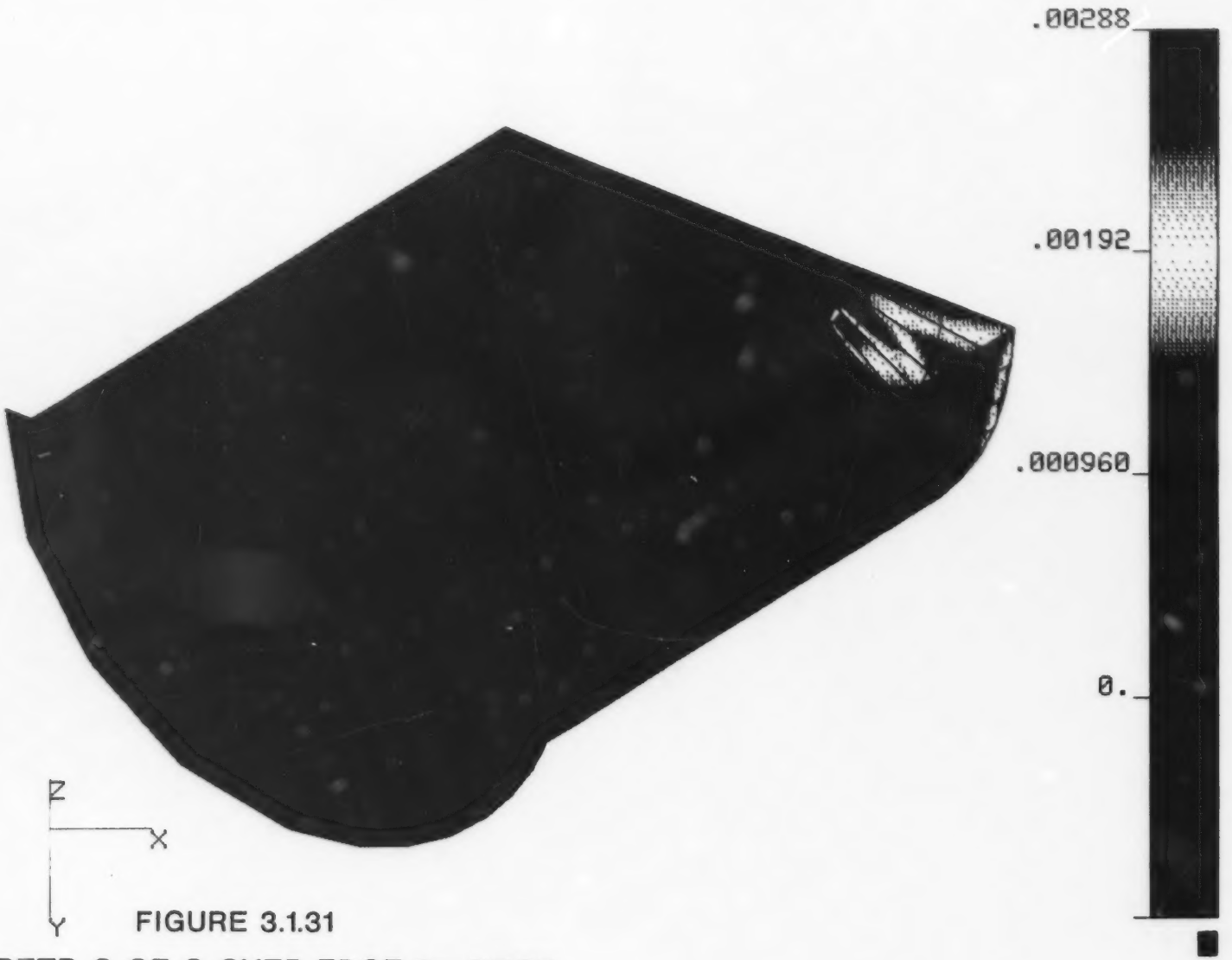


FIGURE 3.1.31

RFTP C OF G OVER EDGE 9m DROP
EFFECTIVE PLASTIC STRAIN ON INSIDE SURFACE

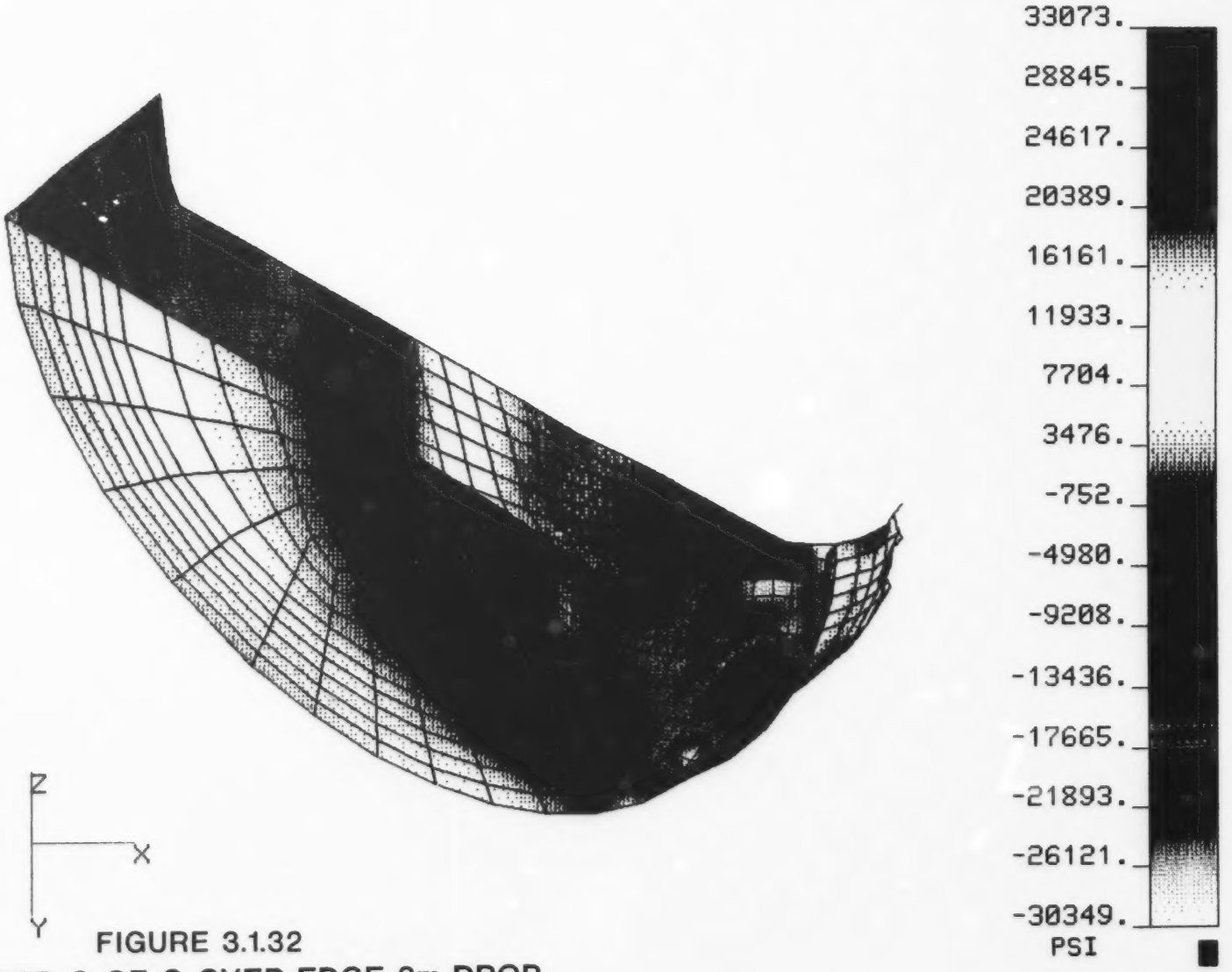


FIGURE 3.1.32
RFTP C OF G OVER EDGE 9m DROP
HYDROSTATIC STRESS, MEMBRANE COMPONENT

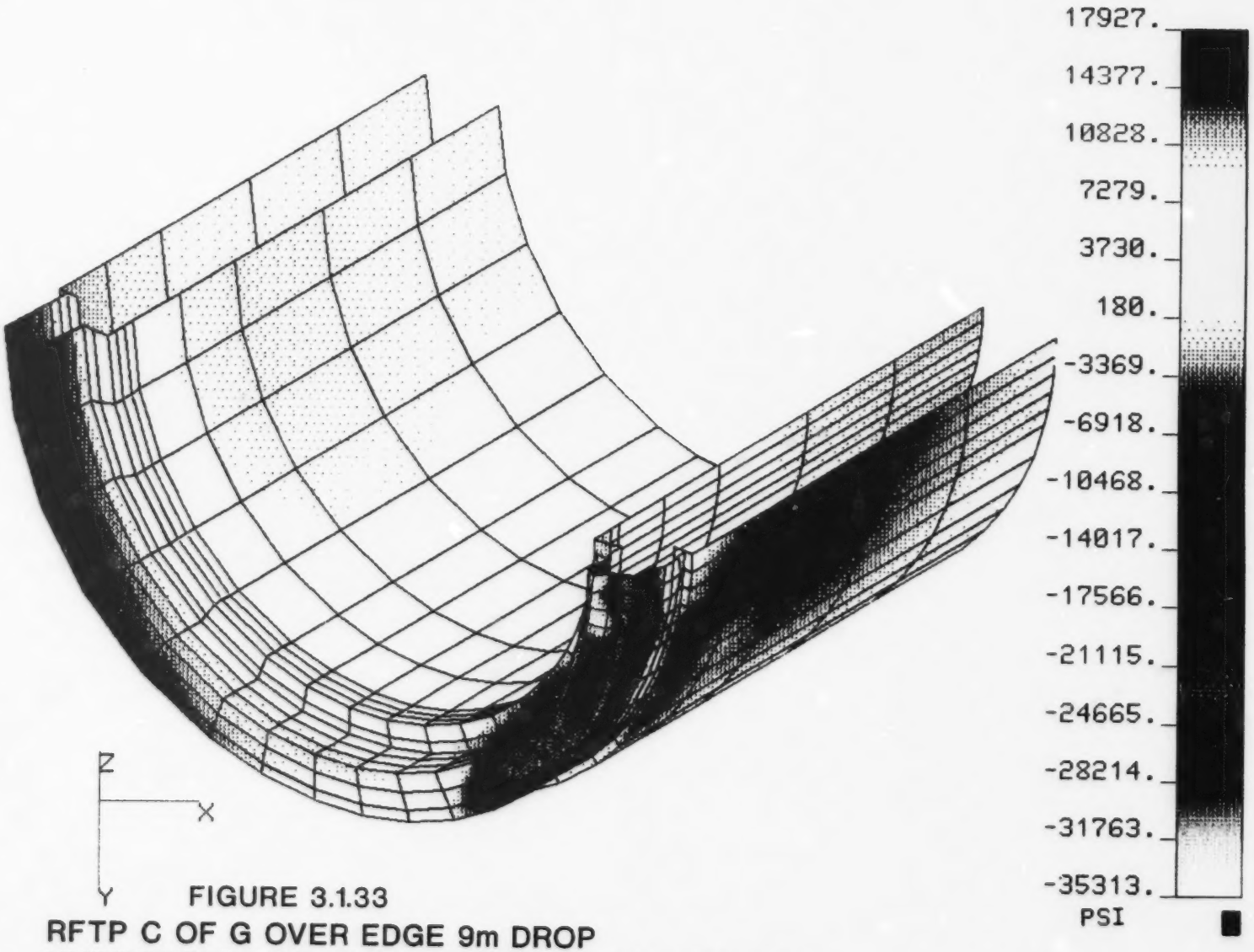


FIGURE 3.1.33
RFTP C OF G OVER EDGE 9m DROP
HYDROSTATIC STRESS, MEMBRANE COMPONENT

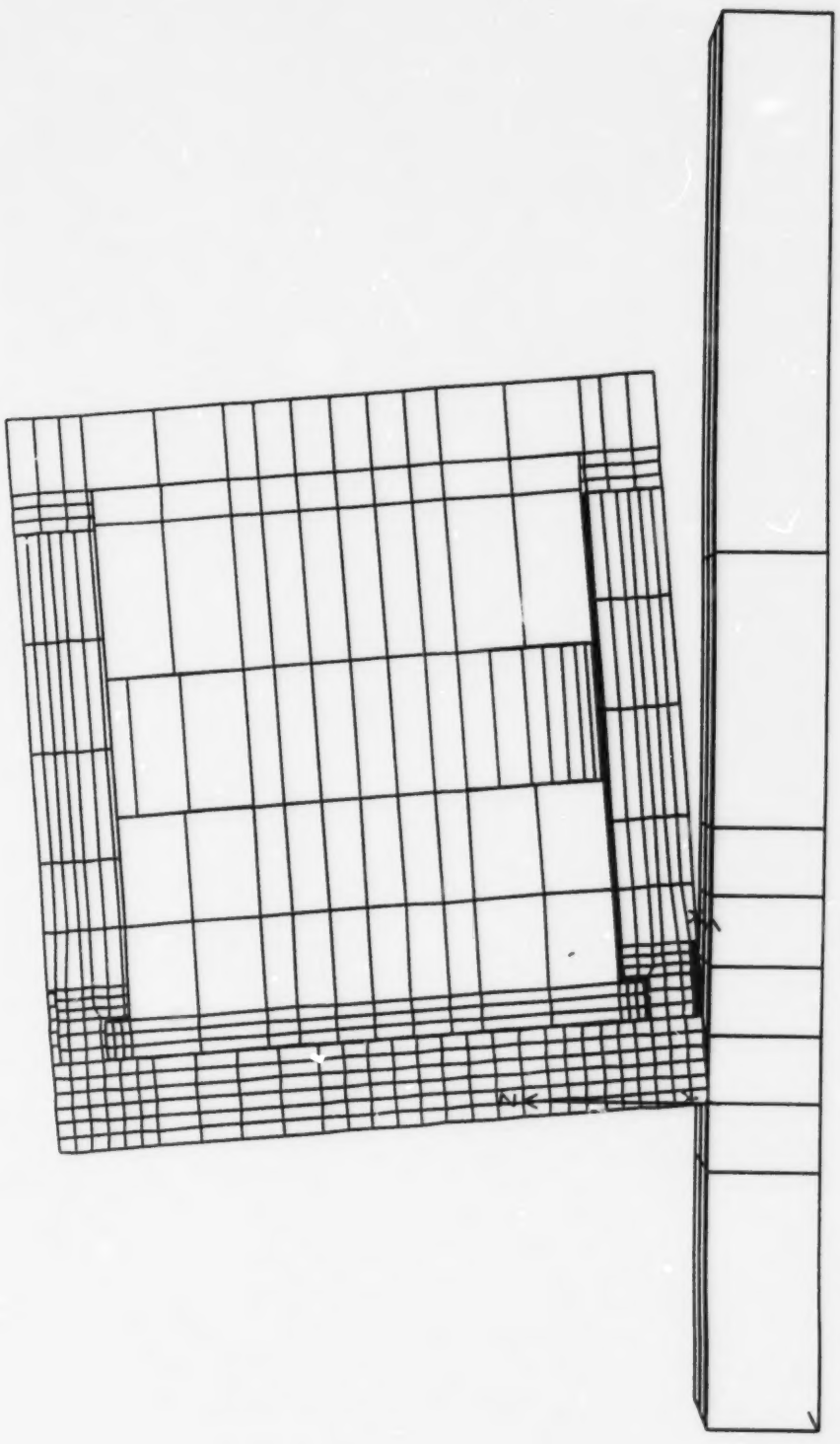


FIGURE 3.2.1
RFTP UNDEFORMED GEOMETRY (SIDE VIEW)

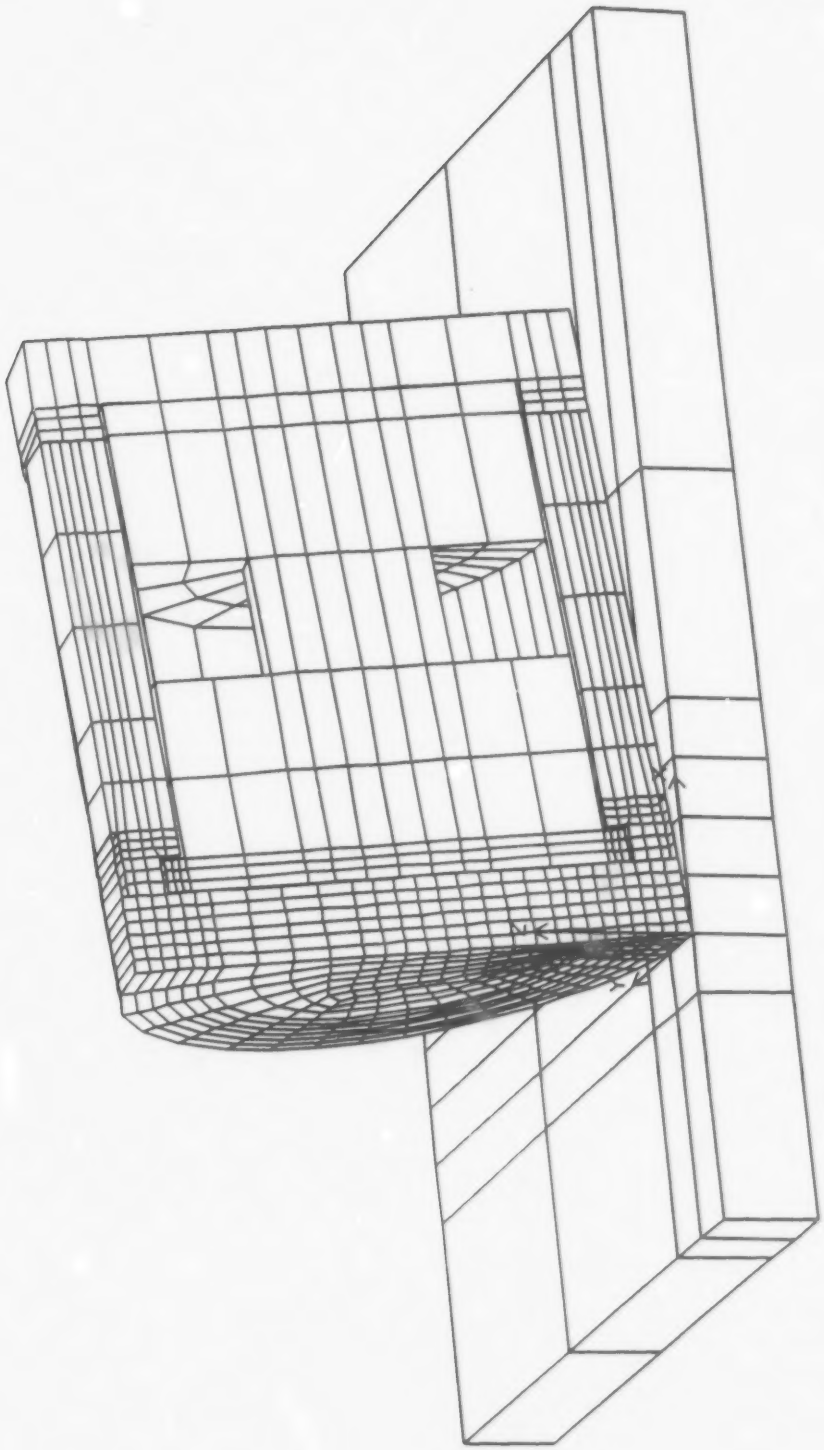


FIGURE 3.2.2
RFTP UNDEFORMED GEOMETRY (OBLIQUE VIEW)

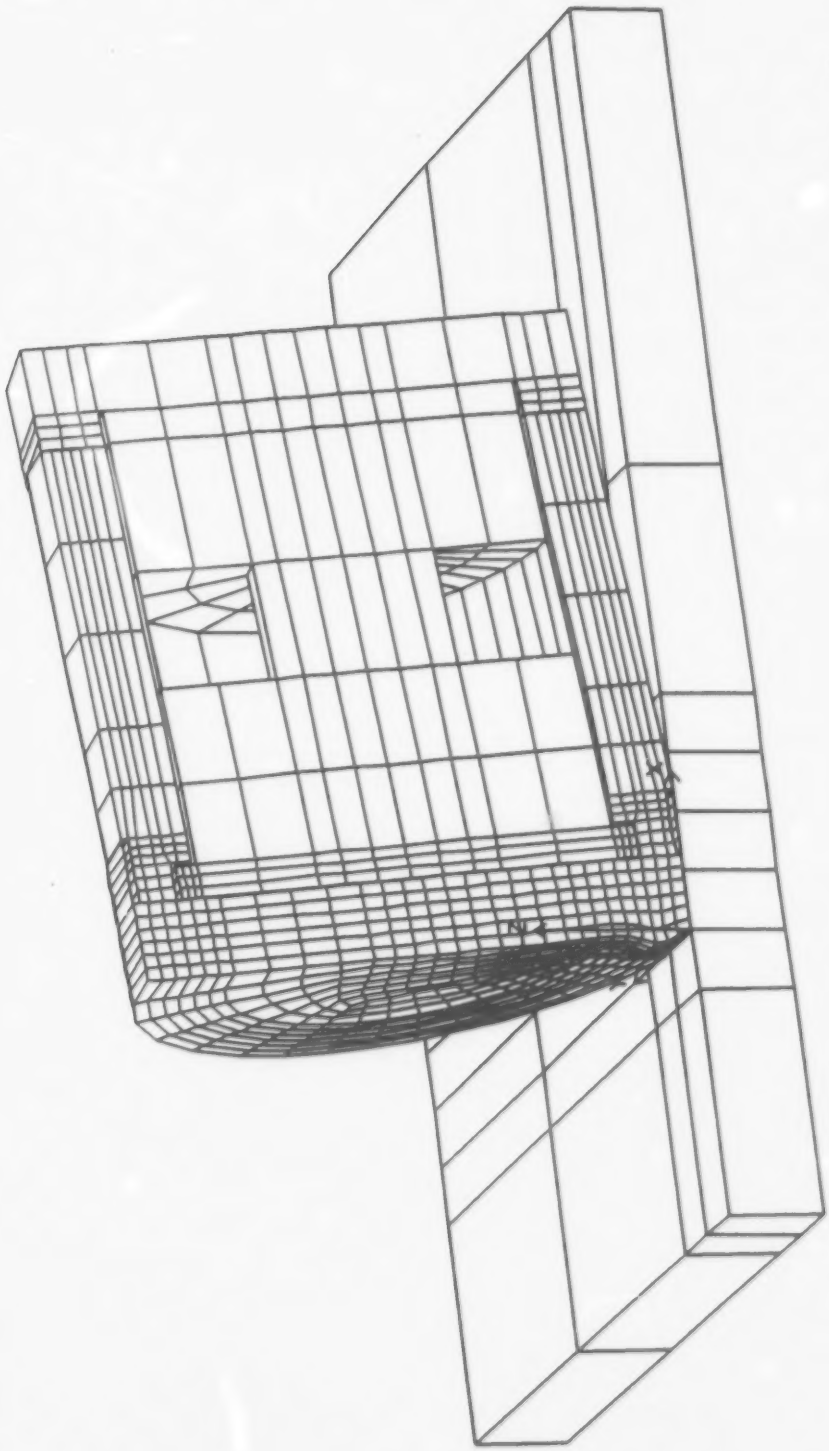


FIGURE 3.2.3
RFTP DEFORMED GEOMETRY (TIME = 1 ms)

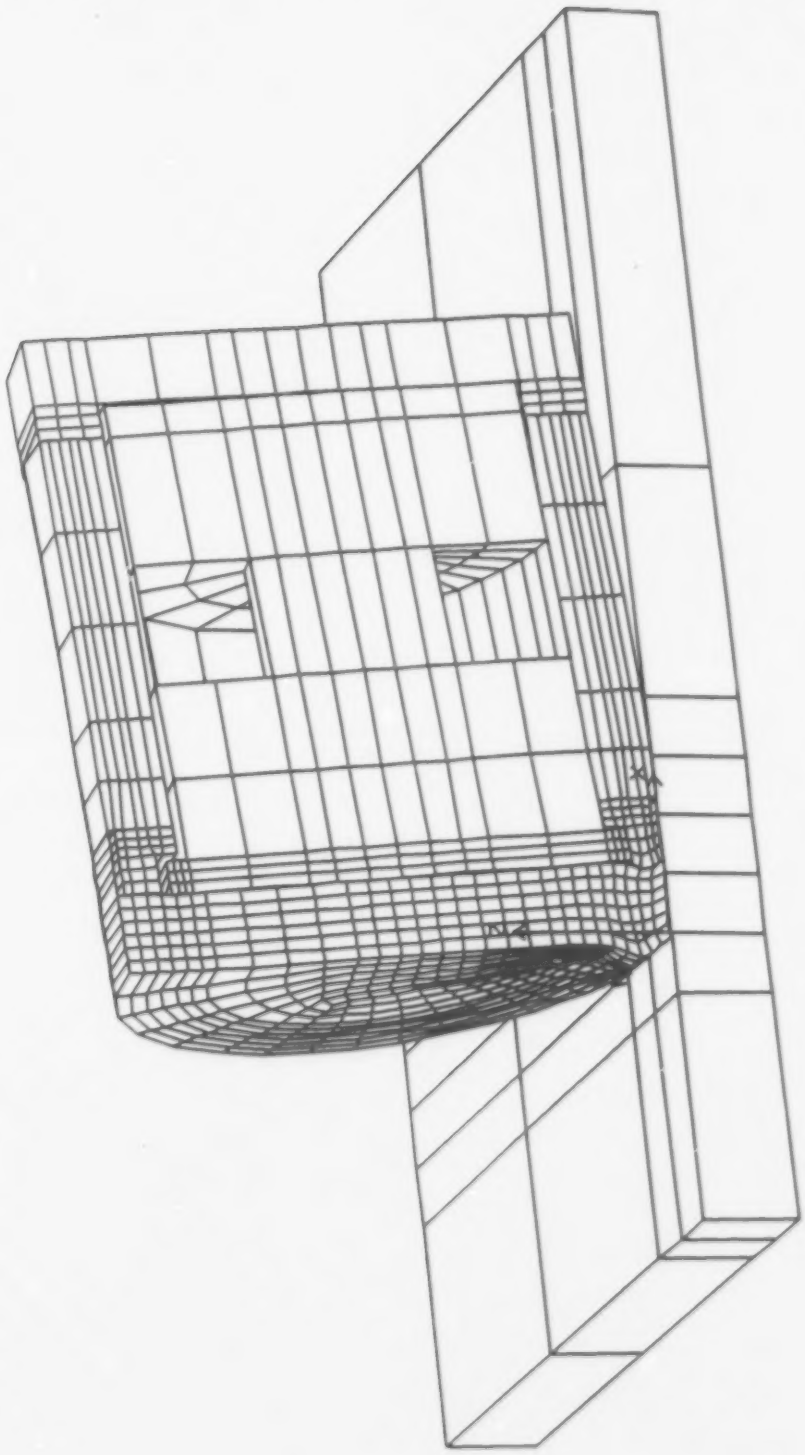


FIGURE 3.2.4
RFTP DEFORMED GEOMETRY (TIME = 2 ms)

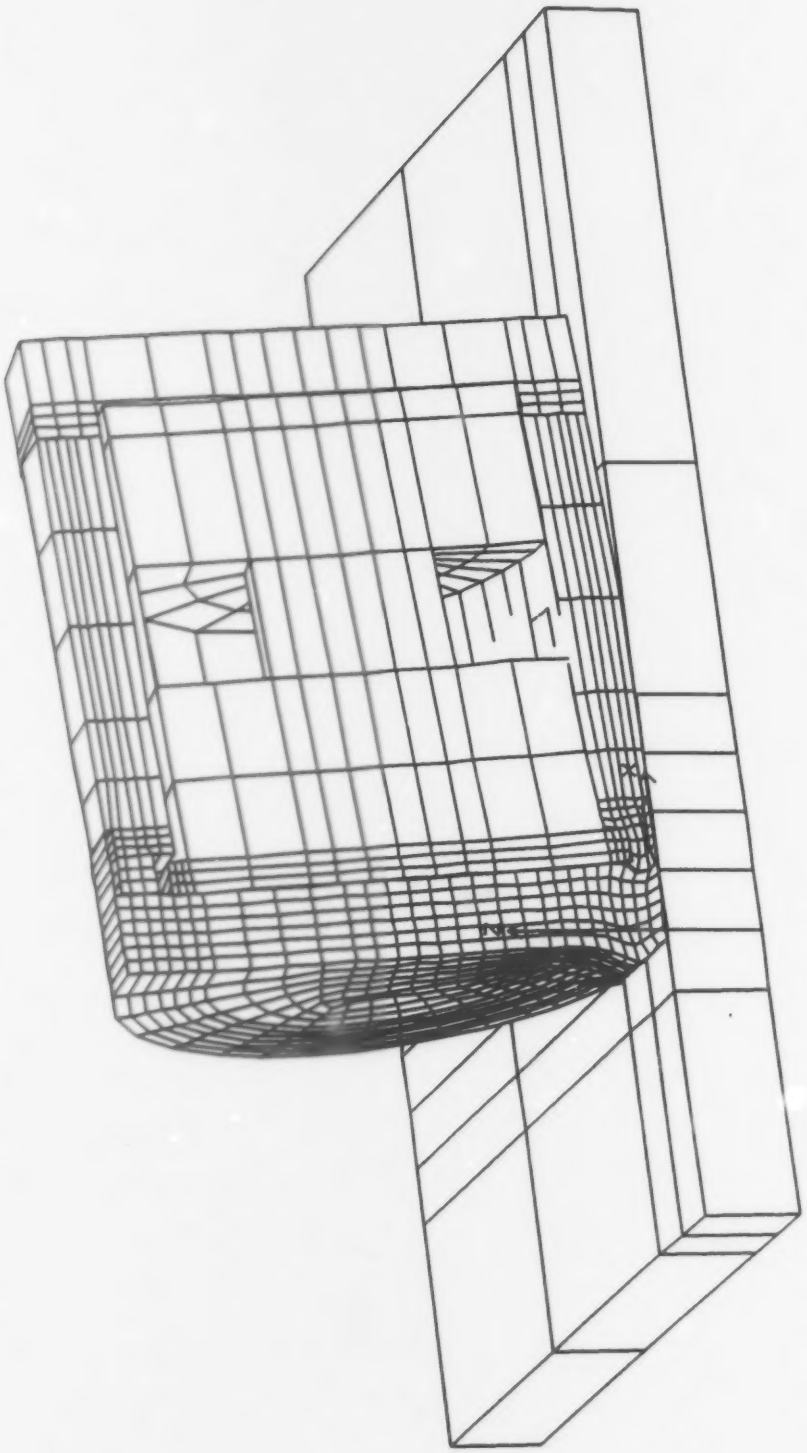


FIGURE 3.2.5
RFTP DEFORMED GEOMETRY (TIME = 3 ms)

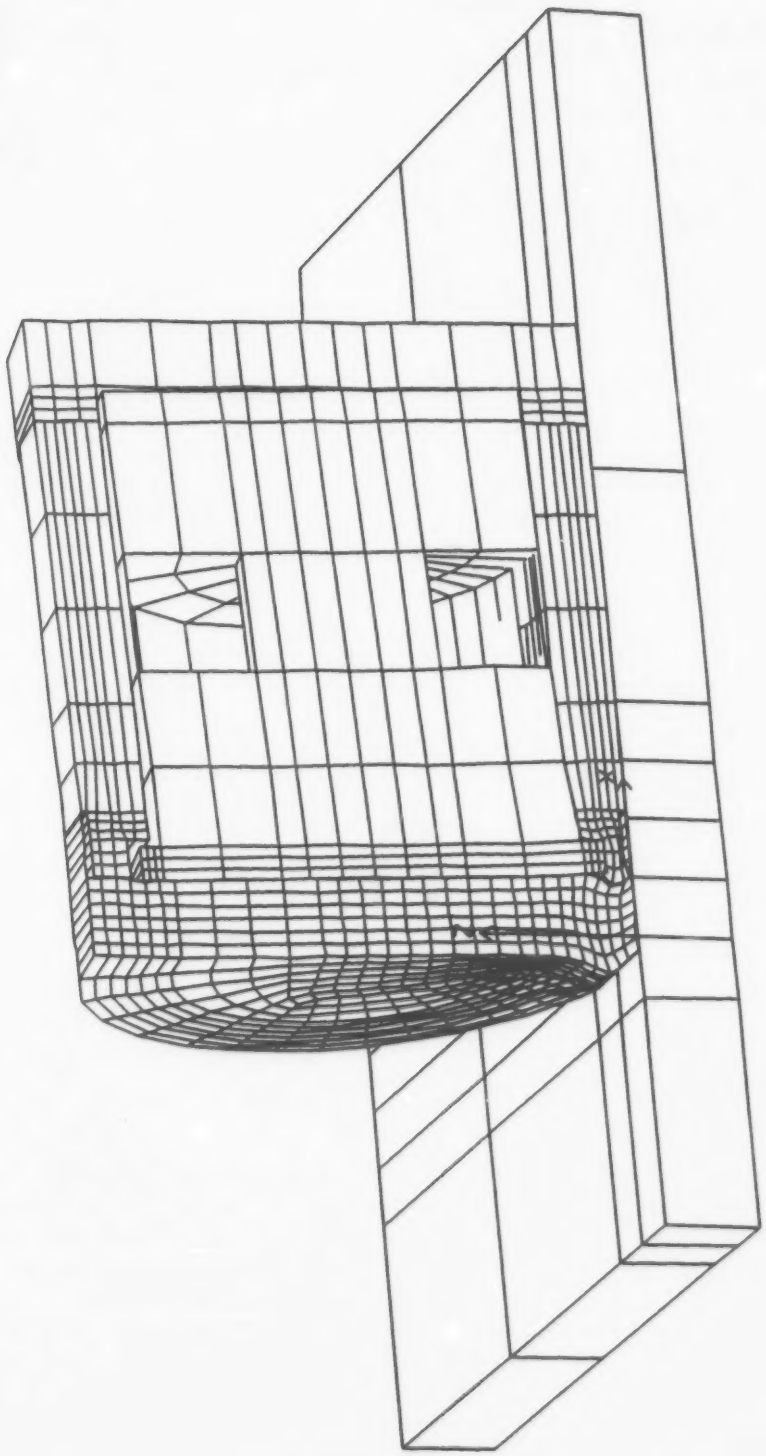


FIGURE 3.2.6
RFTP DEFORMED GEOMETRY (TIME = 4 ms)

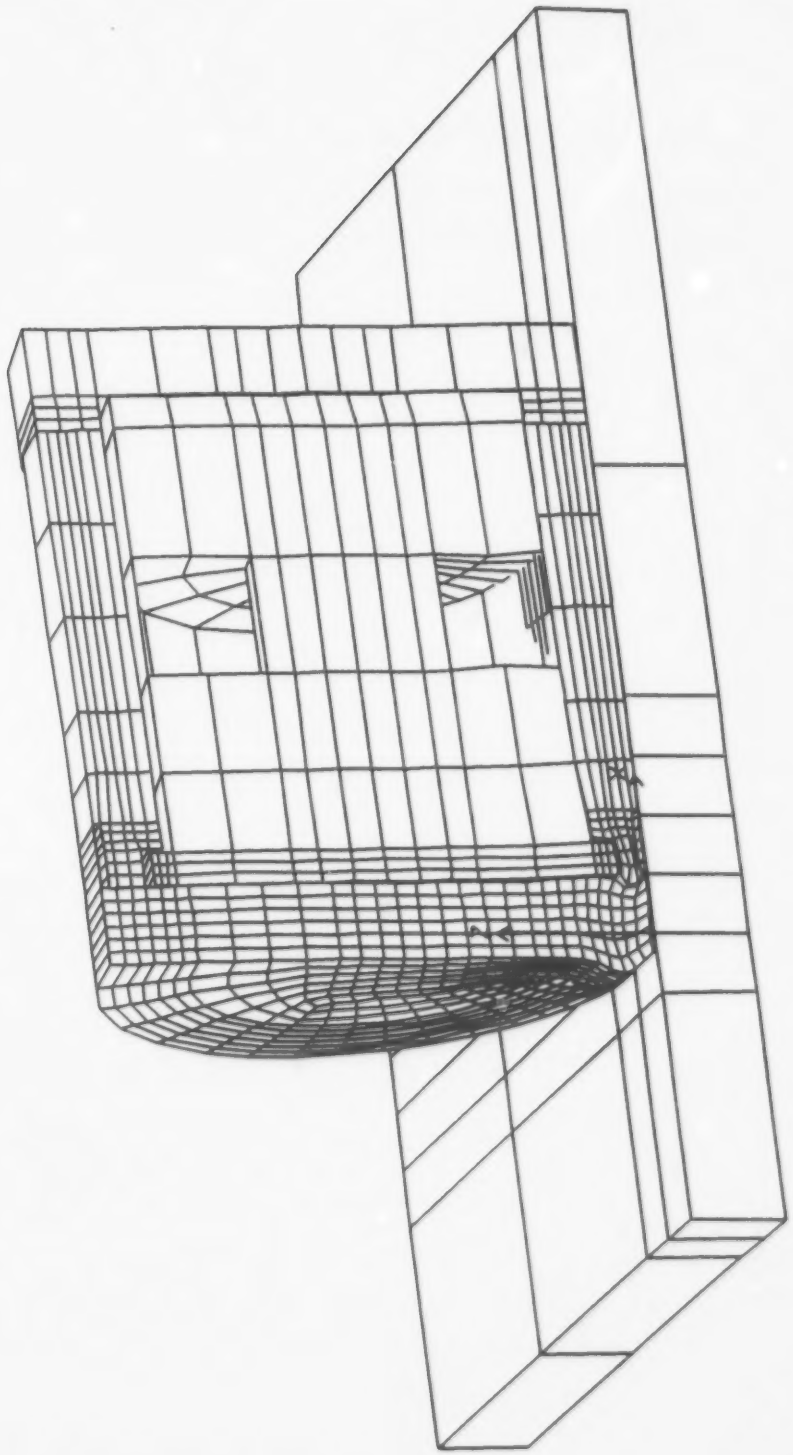


FIGURE 3.2.7
RFTP DEFORMED GEOMETRY (TIME = 5 ms)

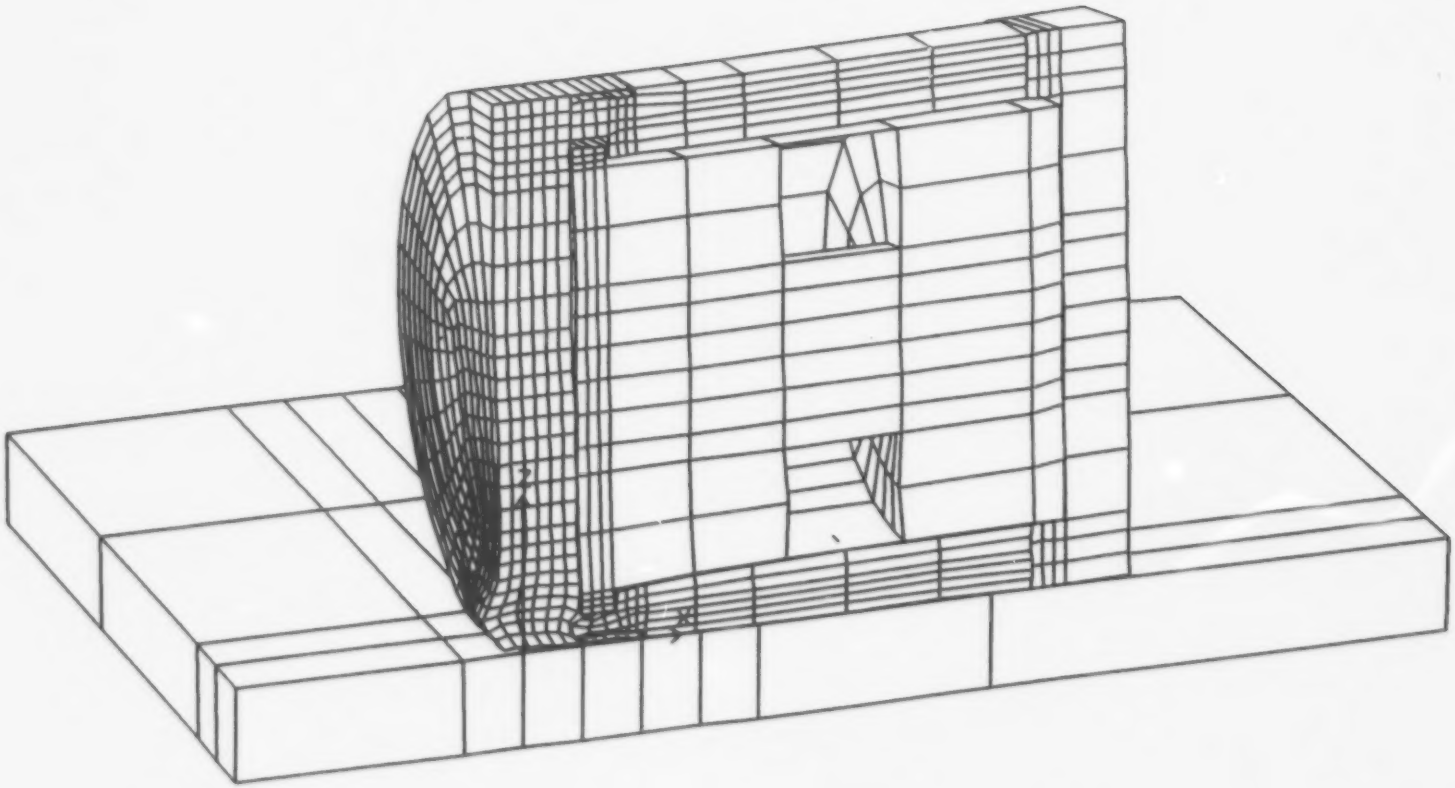


FIGURE 3.2.8
RFTP FINAL DEFORMED GEOMETRY (TIME = 6 ms)

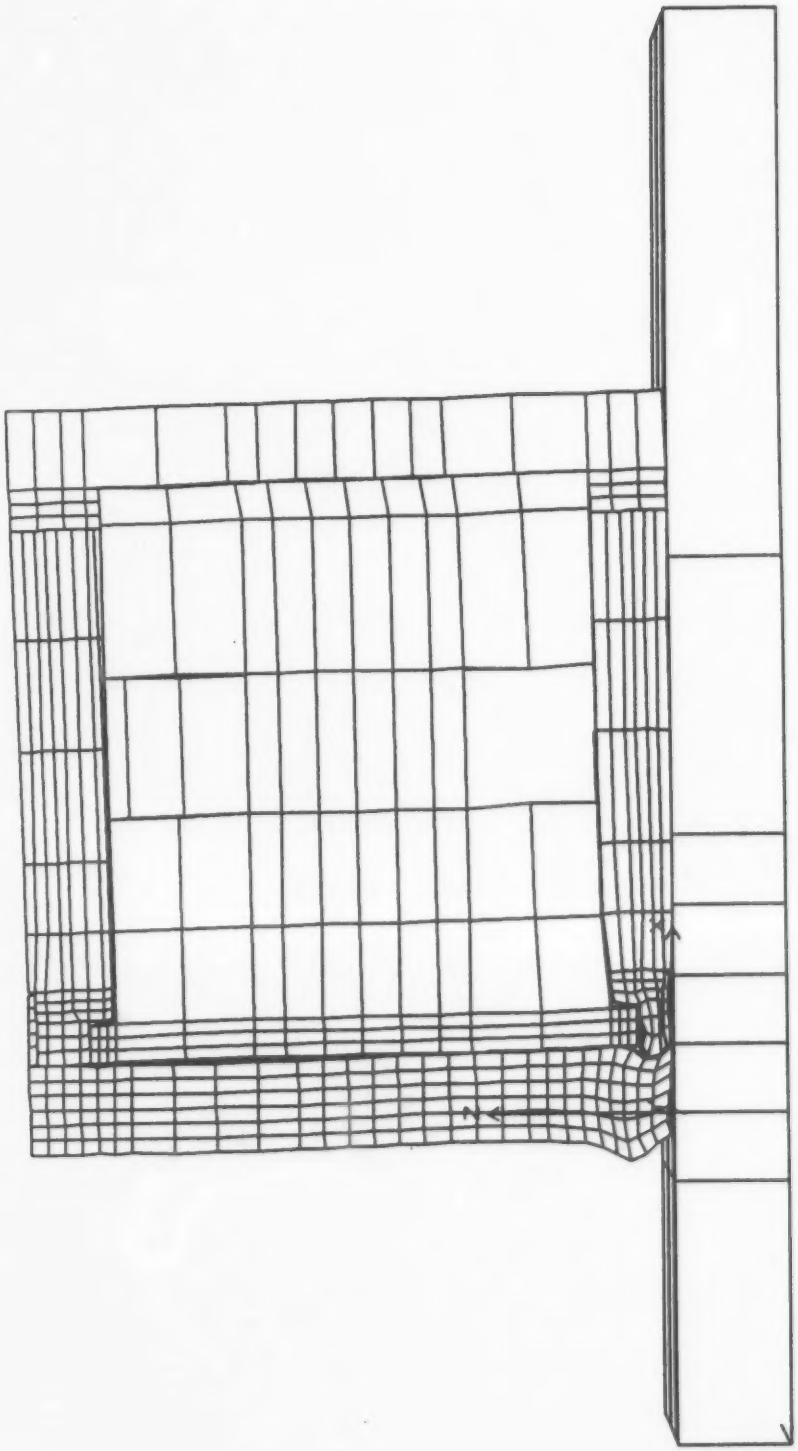


FIGURE 3.2.9
RFTP FINAL DEFORMED GEOMETRY (SIDE VIEW)

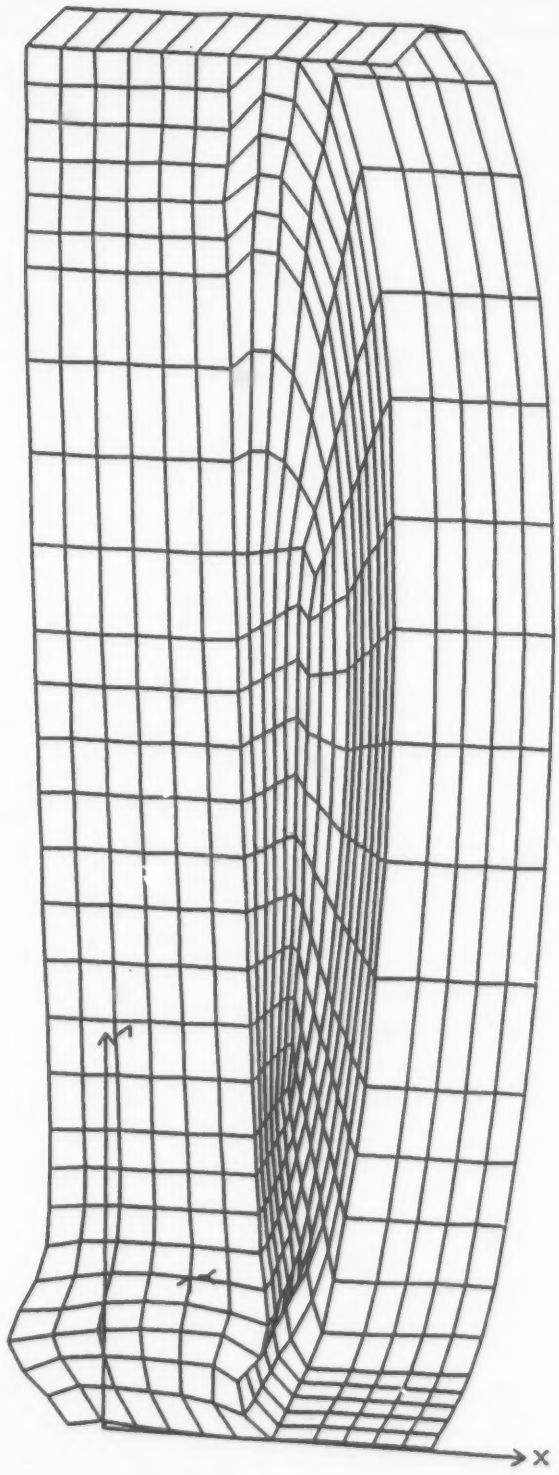


FIGURE 3.2.10
DEFORMED GEOMETRY OF OVERPACK LID

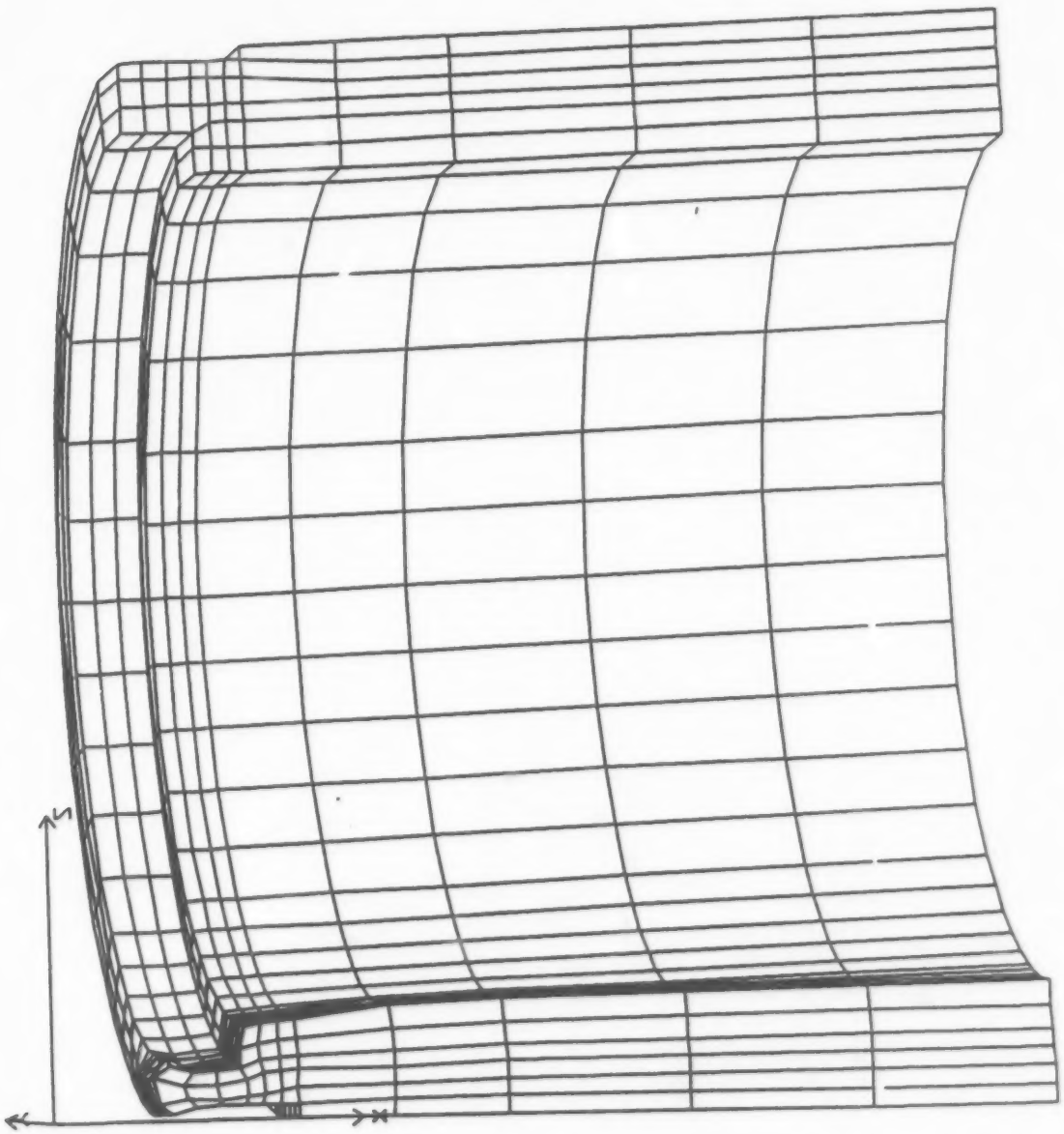


FIGURE 3.2.11
DEFORMED GEOMETRY OF OVERPACK BODY

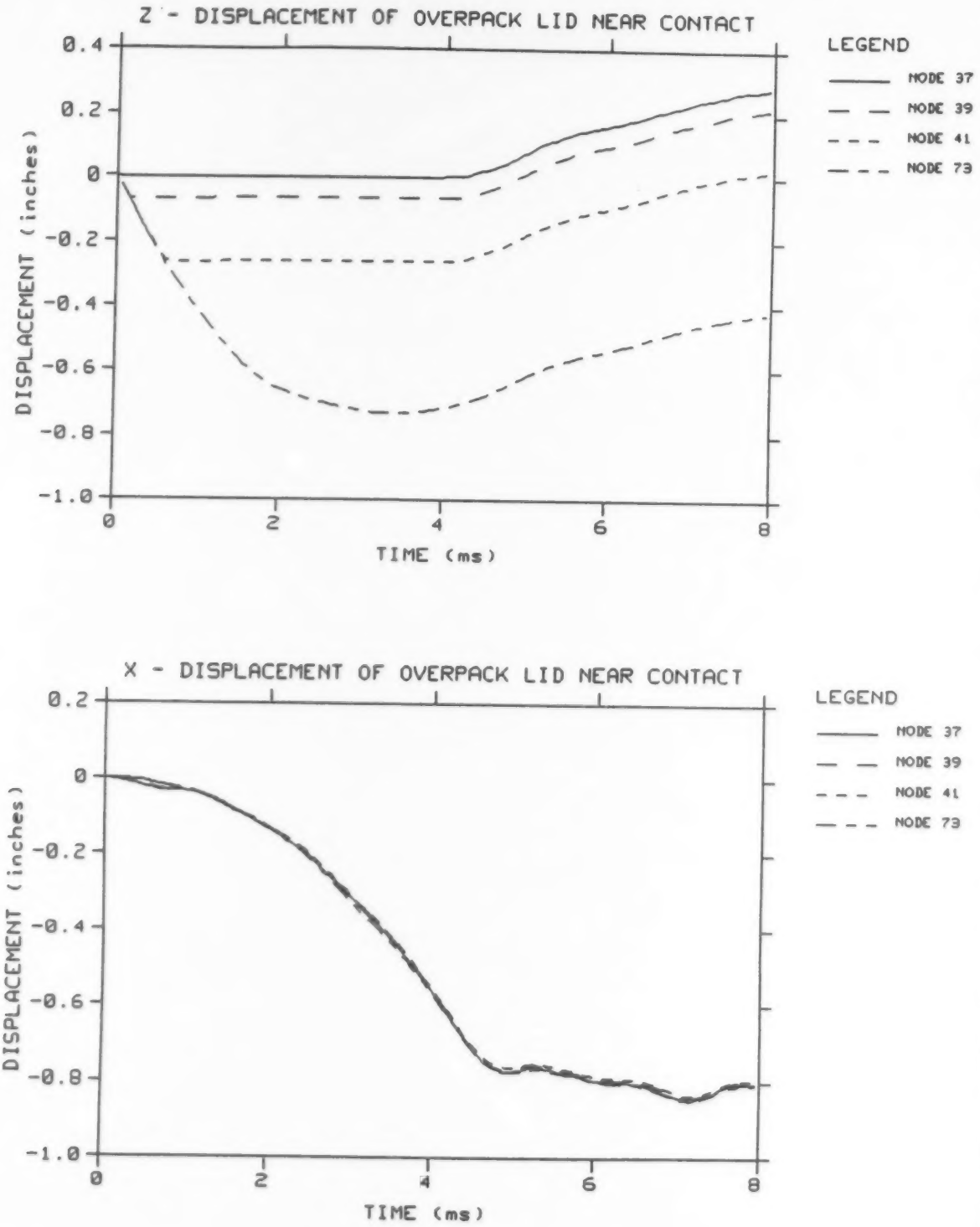
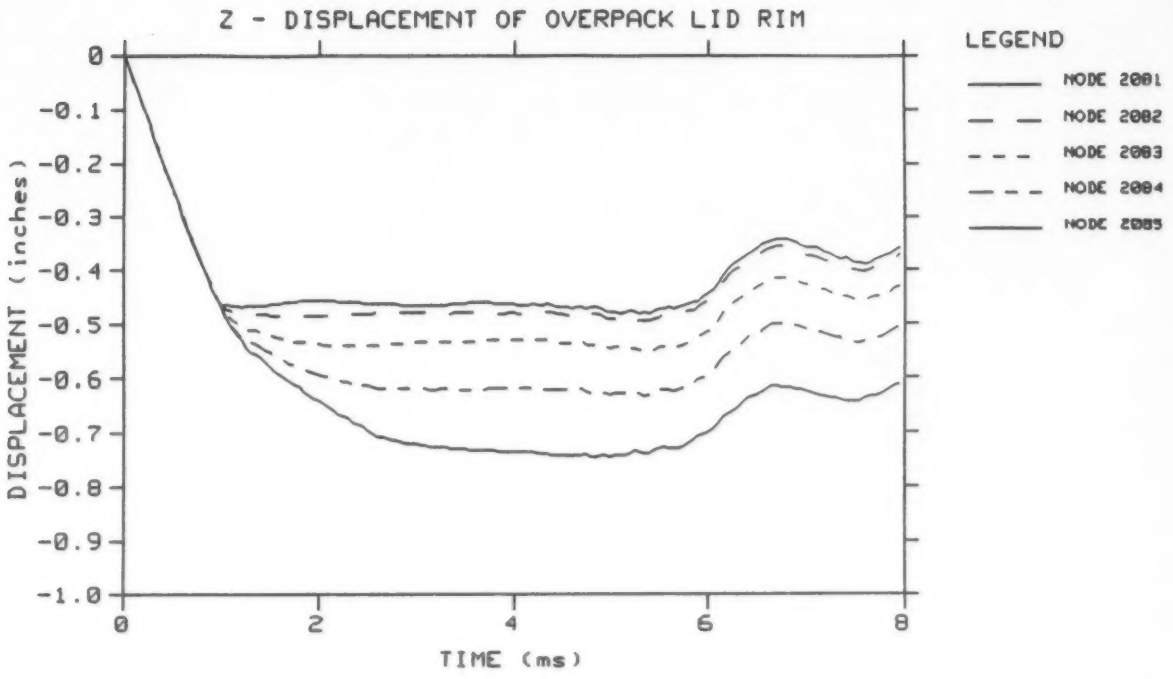


FIGURE 3.2.12
DISPLACEMENT TIME HISTORY OF NODES ON
EDGE OF OVERPACK LID



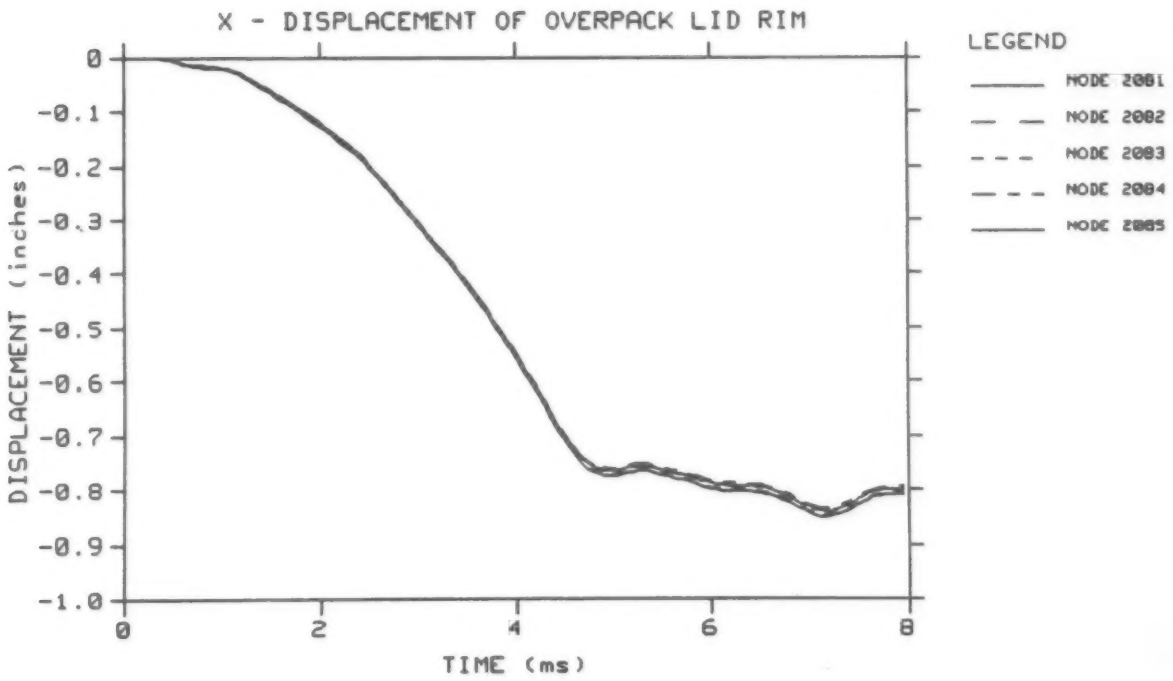
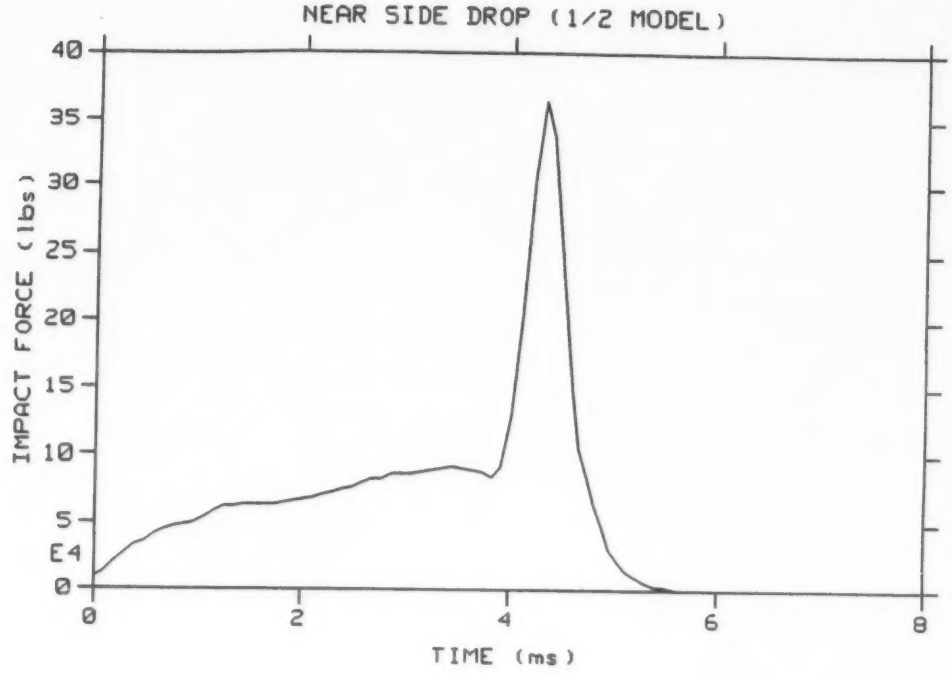
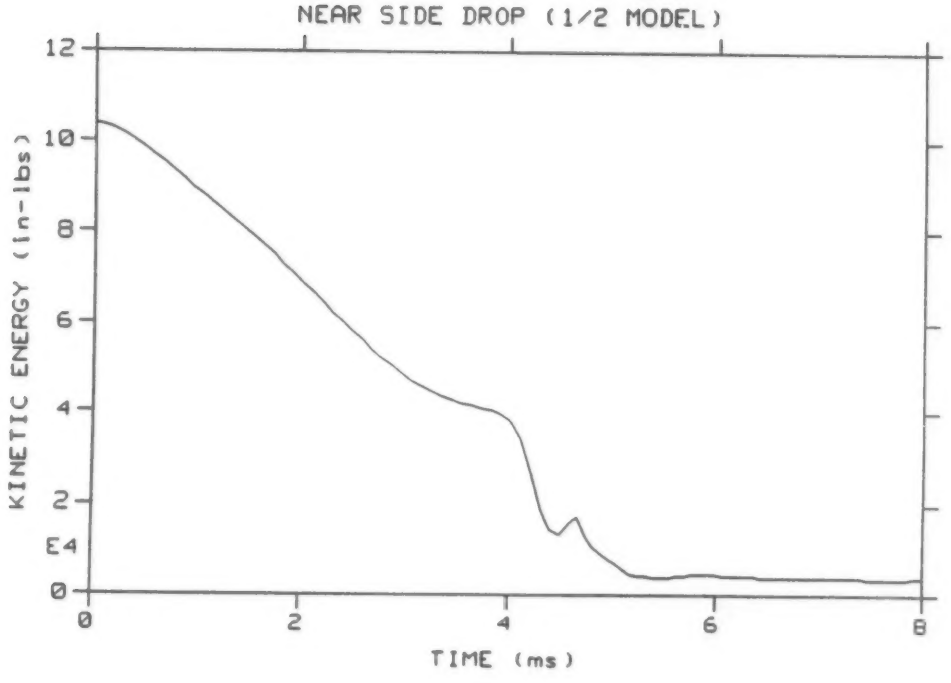


FIGURE 3.2.13
DISPLACEMENT TIME HISTORY OF NODES ON
RIM OF OVERPACK LID

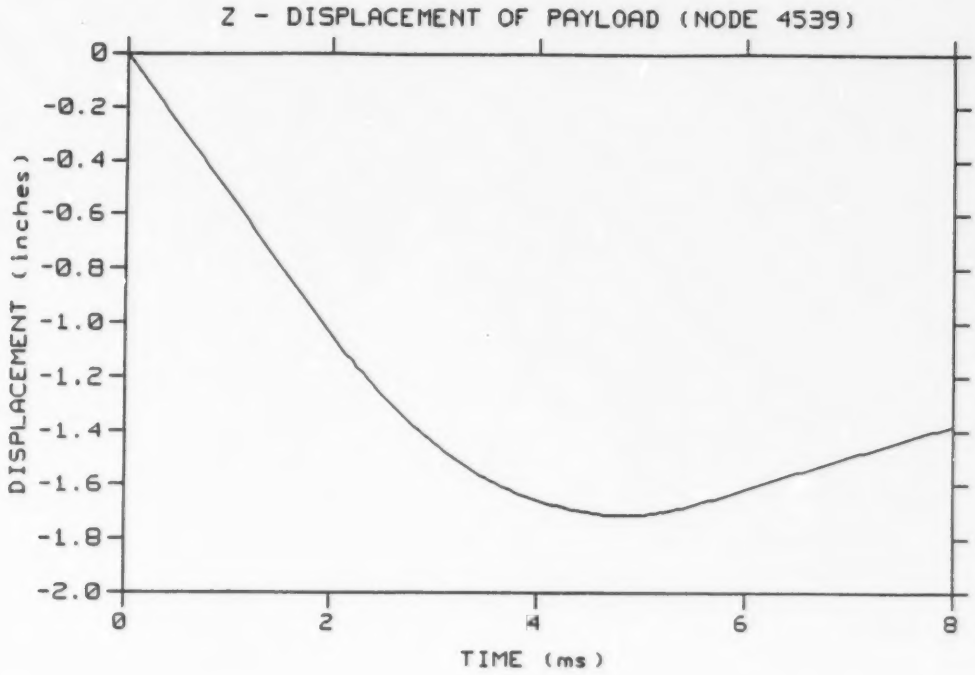


(a)



(b)

FIGURE 3.2.14
TIME HISTORY OF IMPACT FORCE AND KINETIC ENERGY



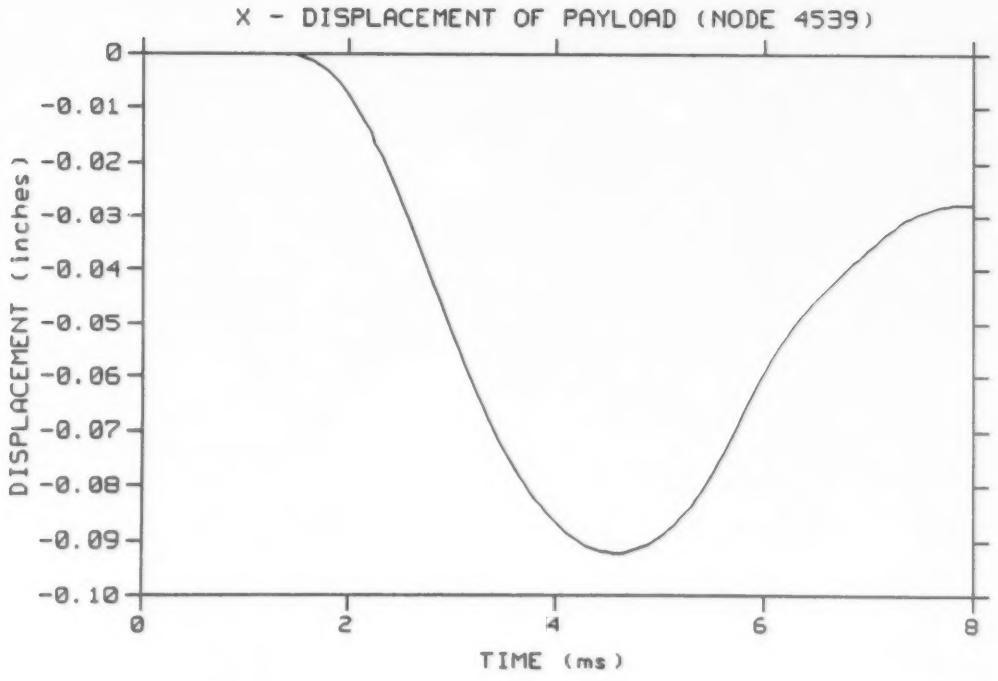
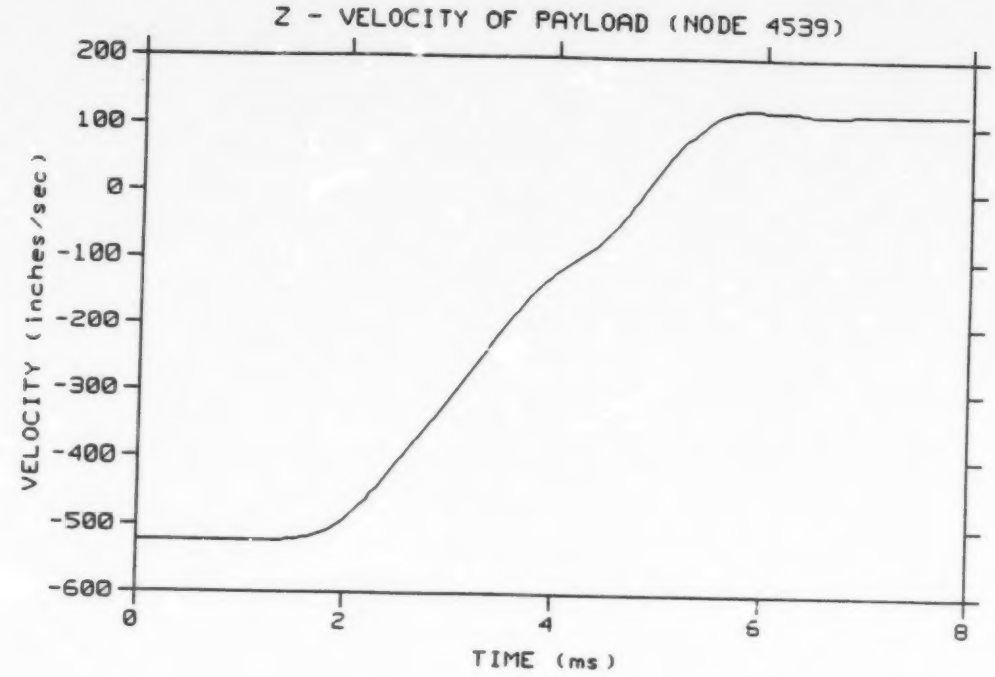


FIGURE 3.2.15
DISPLACEMENT TIME HISTORY OF PAYLOAD



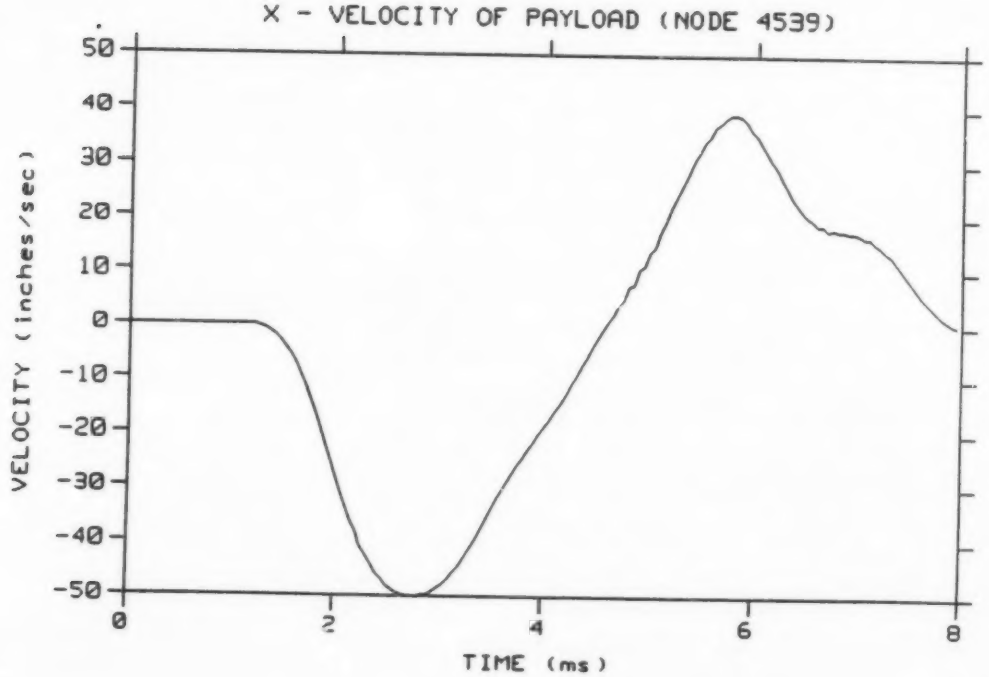
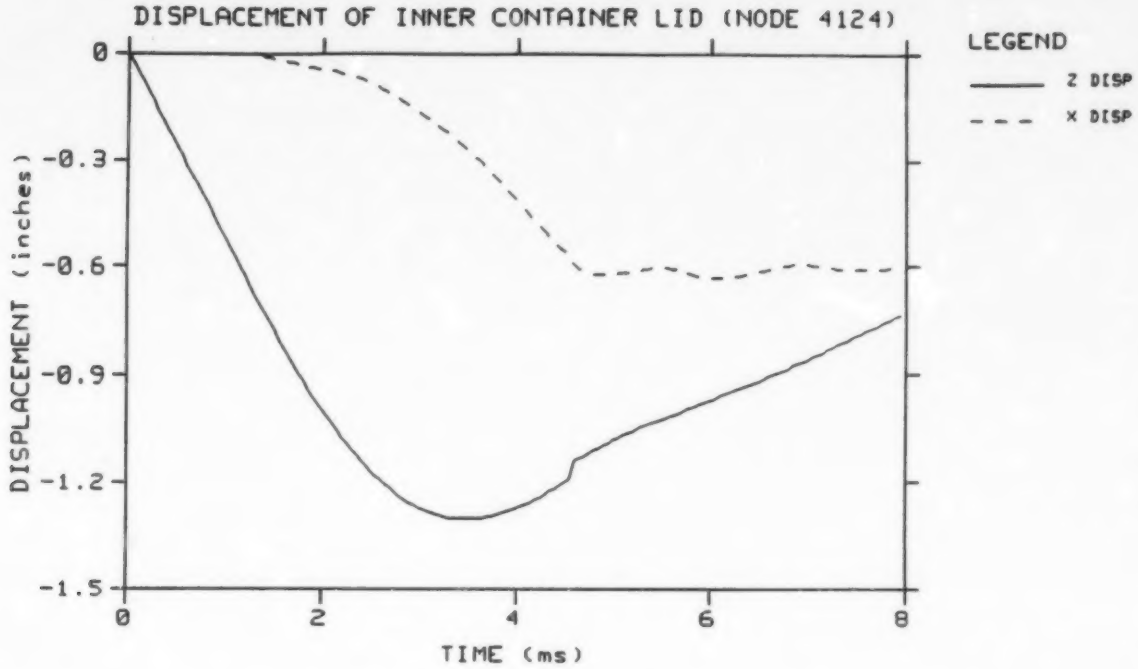


FIGURE 3.2.16
VELOCITY TIME HISTORY OF PAYLOAD



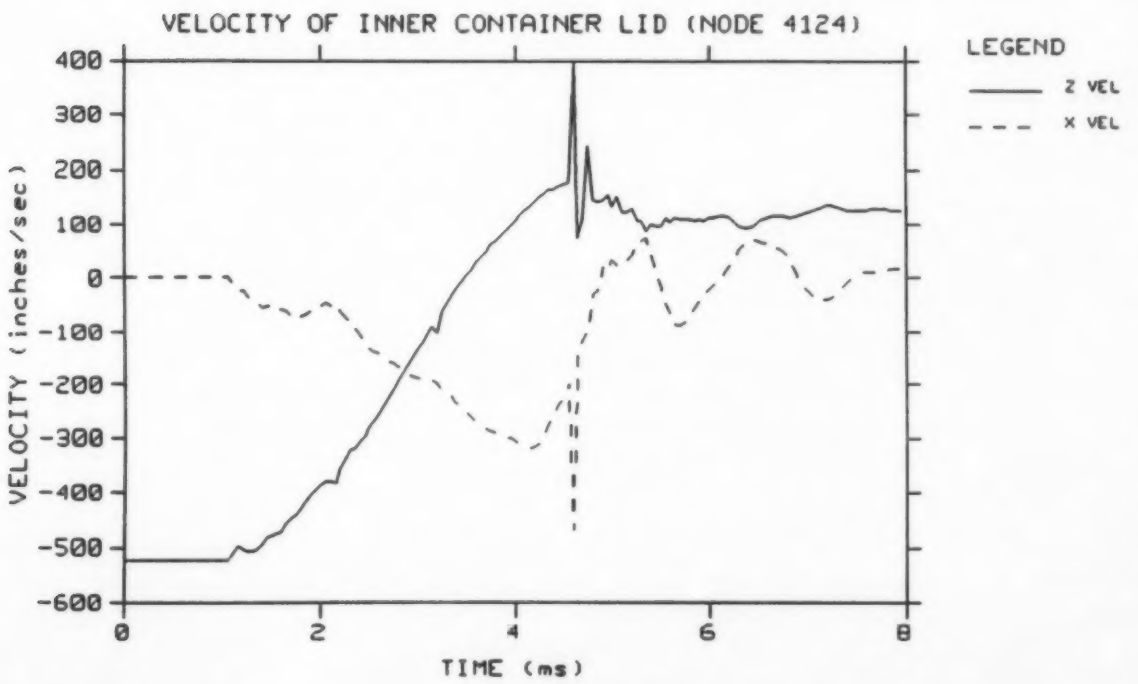
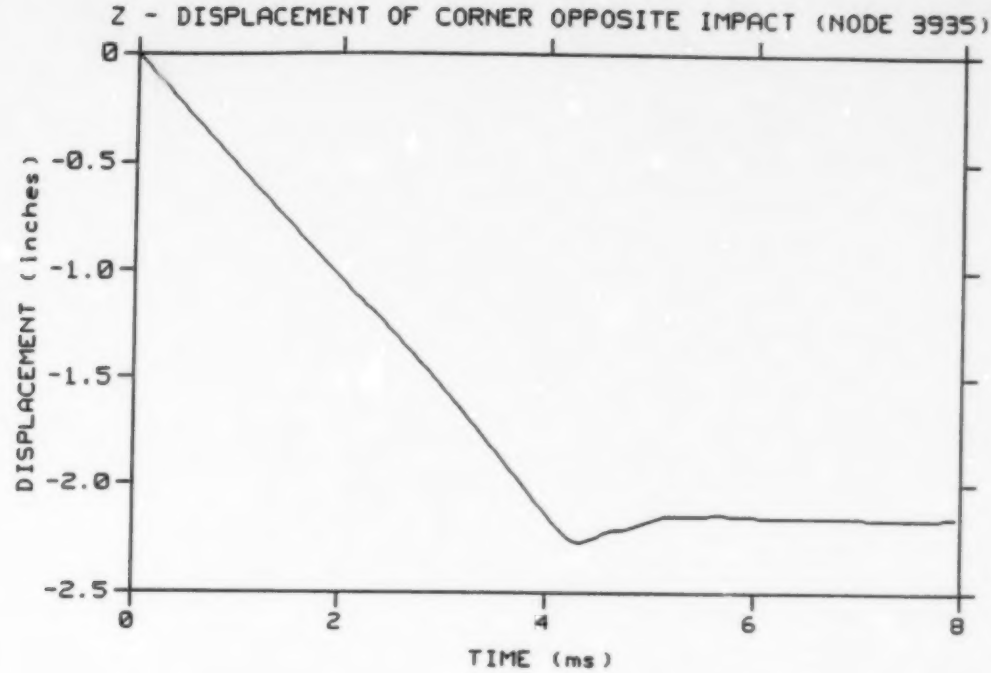


FIGURE 3.2.17
DISPLACEMENT AND VELOCITY TIME HISTORY OF INNER CONTAINER LID



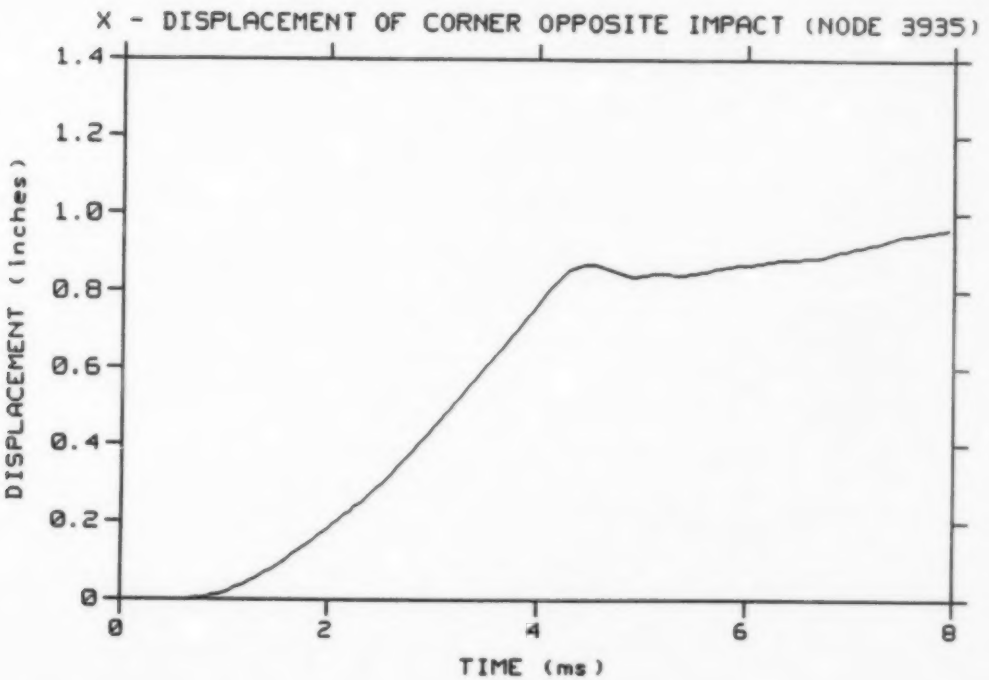


FIGURE 3.2.18
DISPLACEMENT TIME HISTORY OF
CORNER OPPOSITE IMPACT

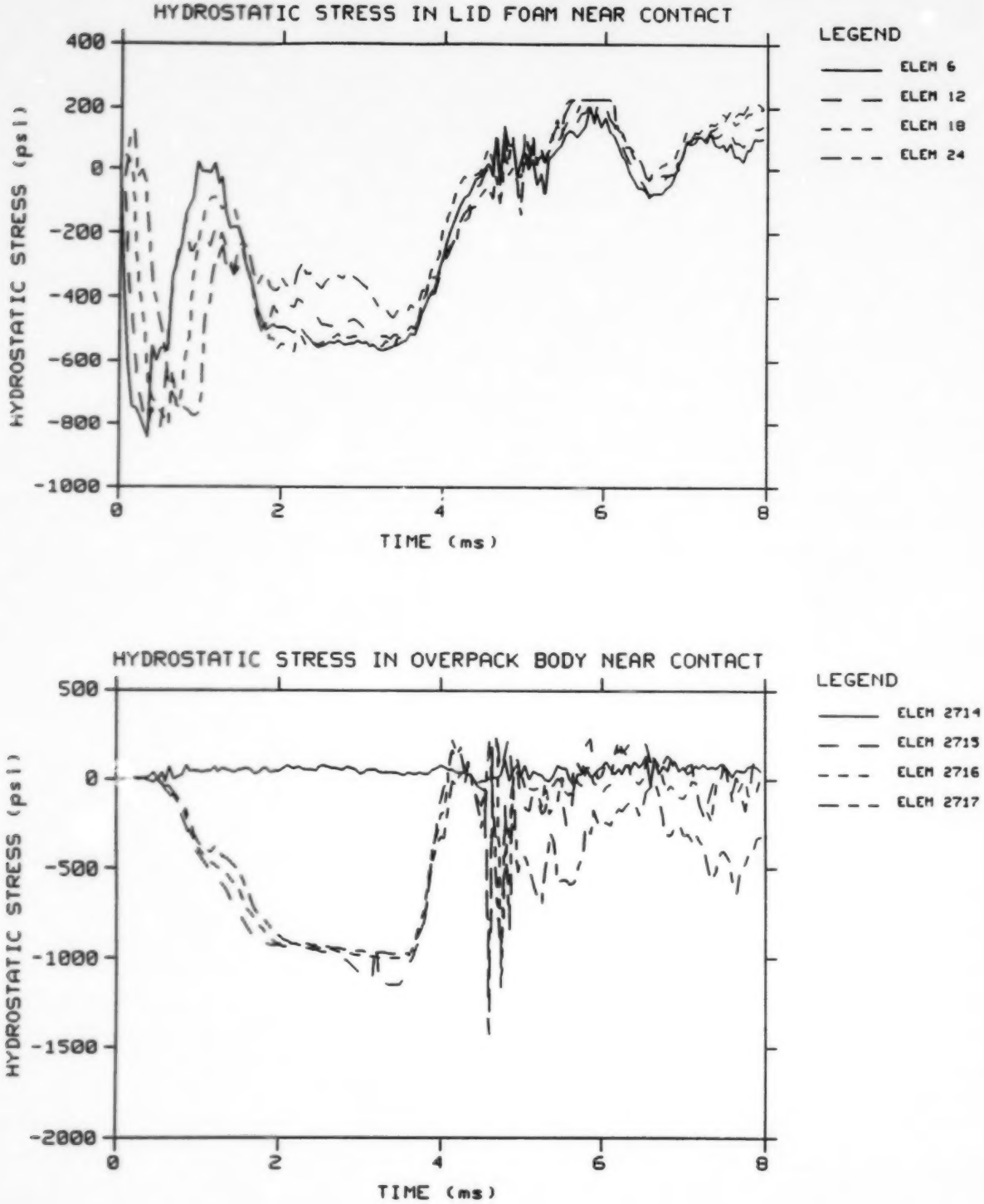
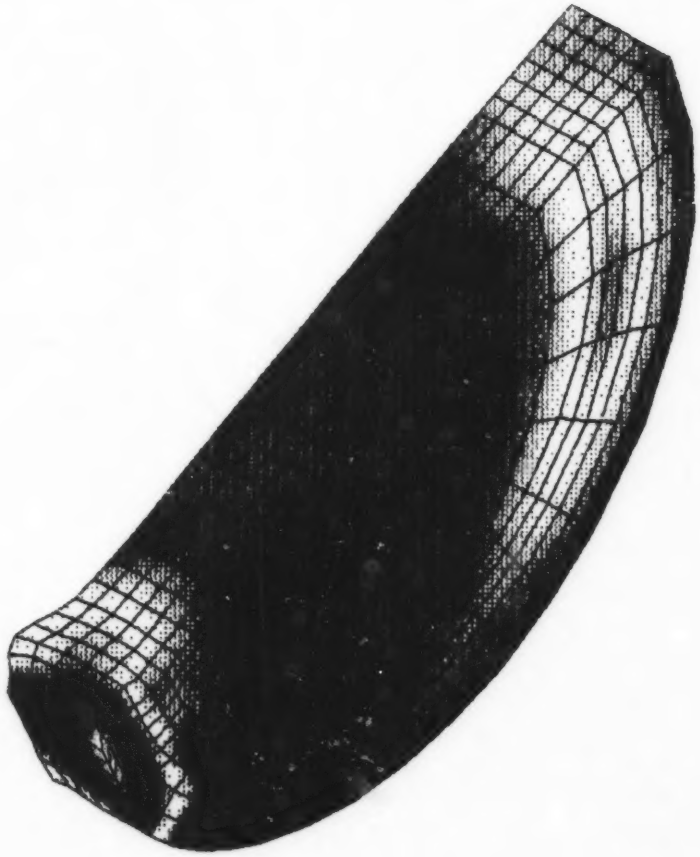
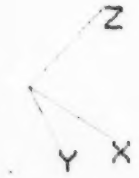


FIGURE 3.2.19
HYDROSTATIC STRESS TIME HISTORY IN
OVERPACK LID AND BODY FOAM





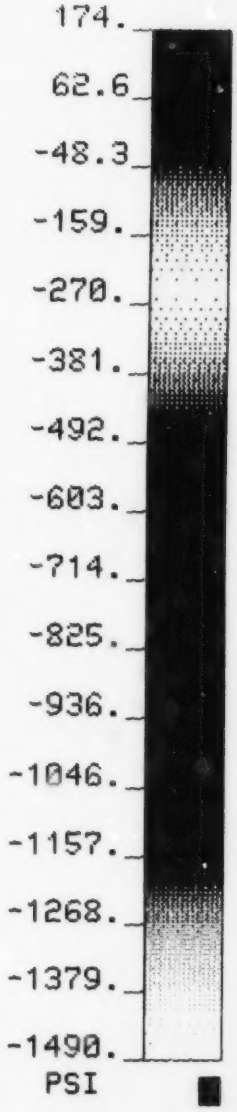


FIGURE 3.2.20
RFTP NEAR SIDE 9m DROP
HYDROSTATIC STRESS AT TIME = 3 ms

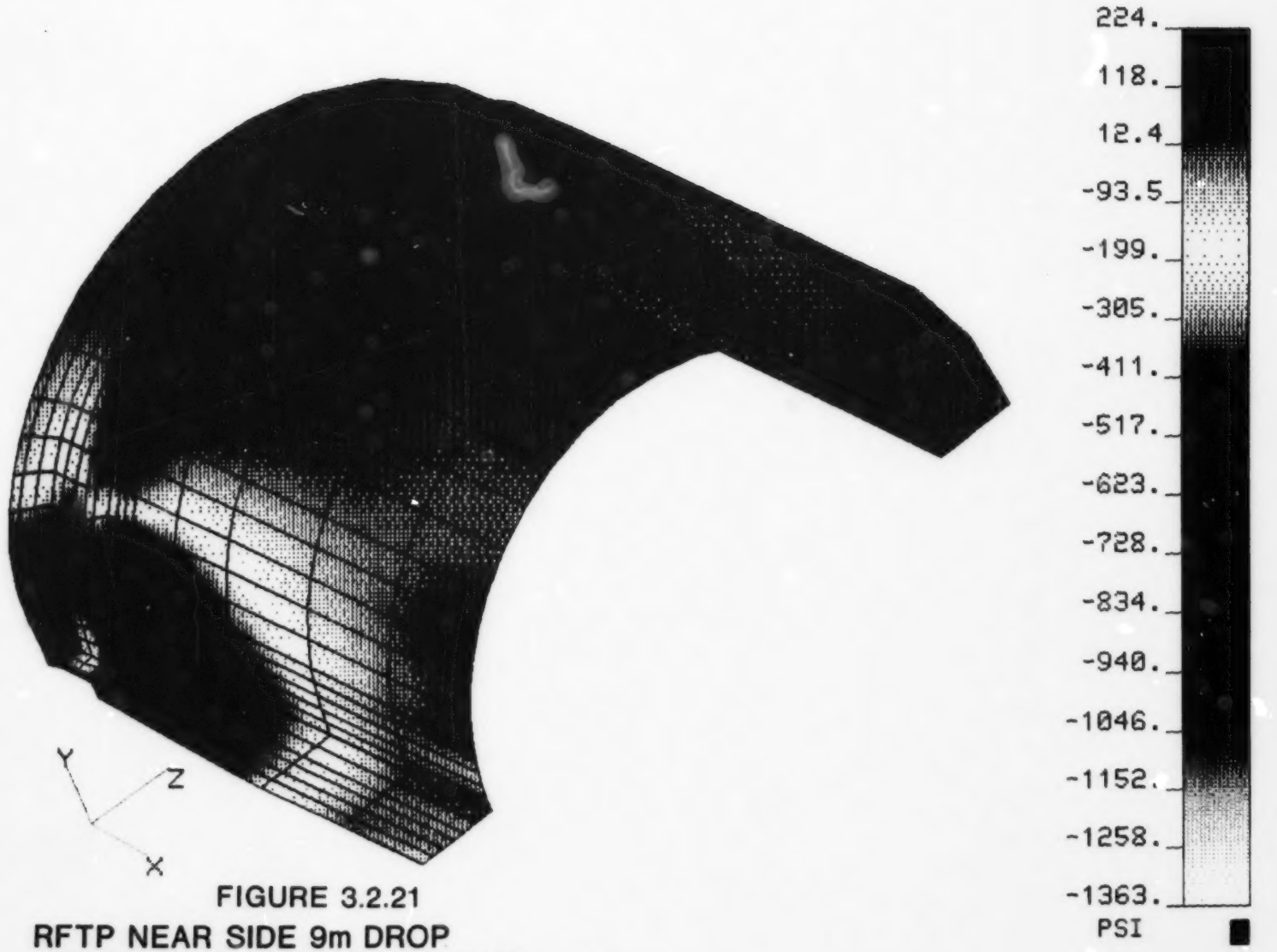


FIGURE 3.2.21
RFTP NEAR SIDE 9m DROP
HYDROSTATIC STRESS AT TIME = 3 ms

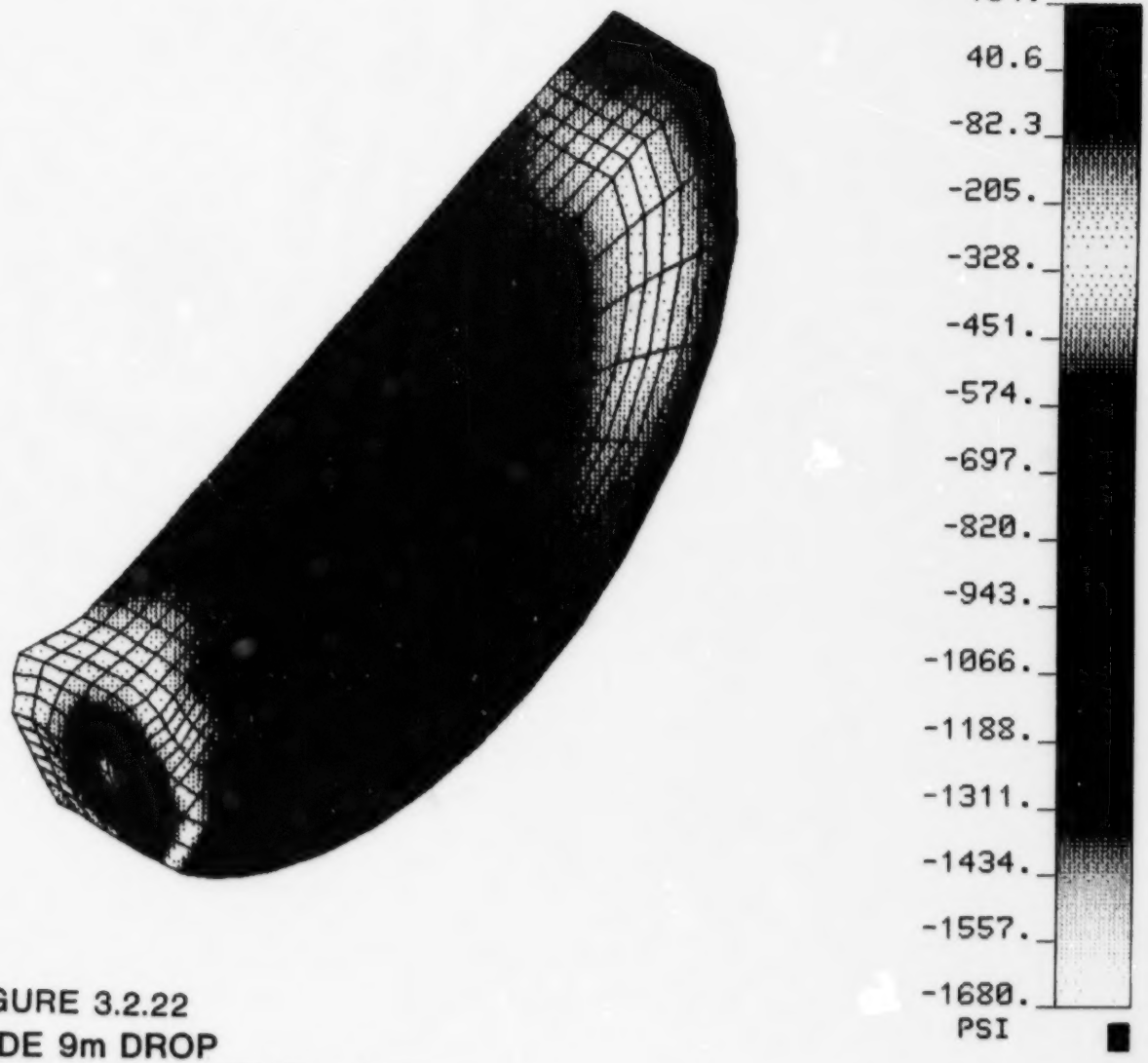


FIGURE 3.2.22
RFTP NEAR SIDE 9m DROP
HYDROSTATIC STRESS AT TIME = 4 ms

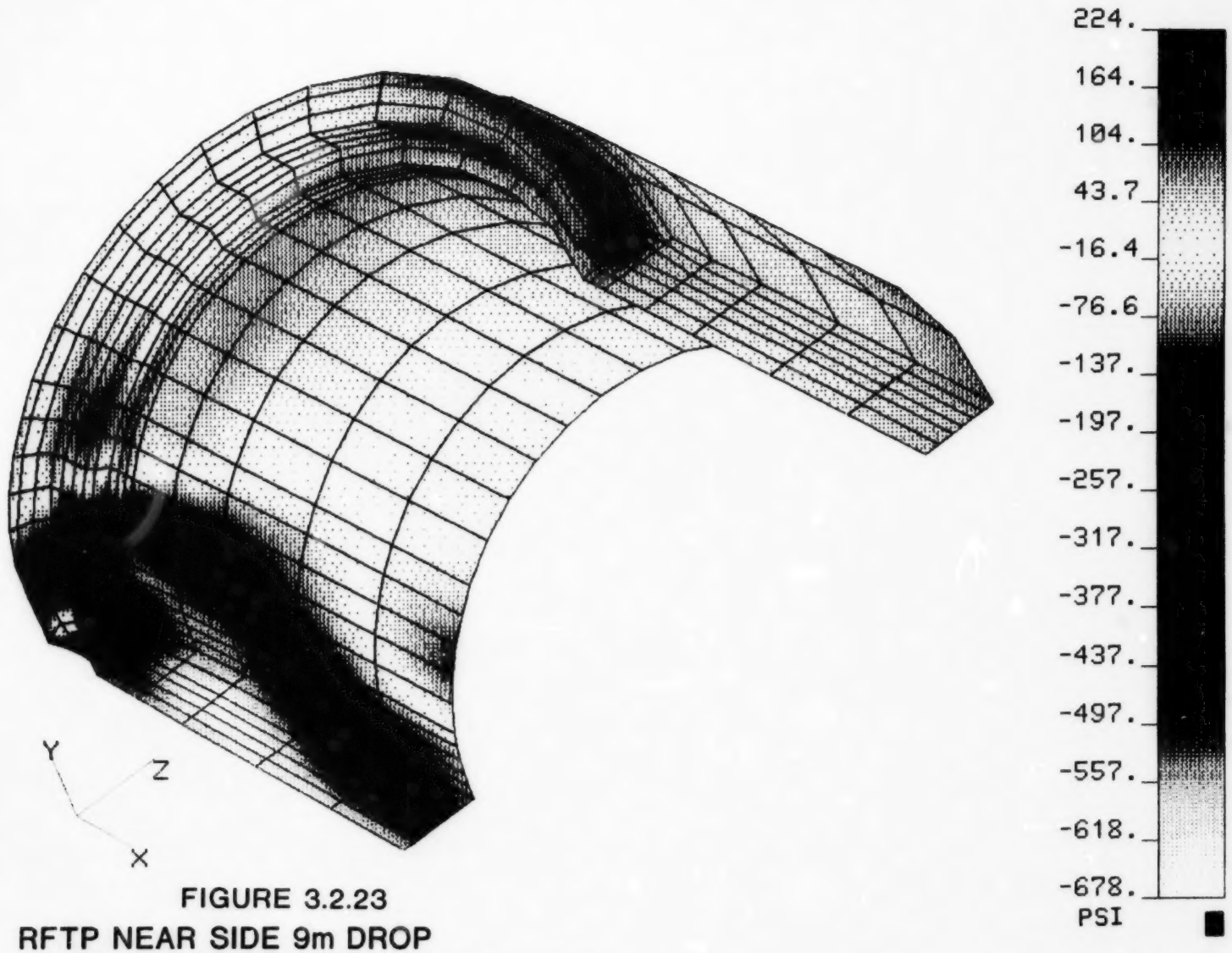


FIGURE 3.2.23
RFTP NEAR SIDE 9m DROP
HYDROSTATIC STRESS AT TIME = 4 ms

FIGURE 3.2.24

RFTP NEAR SIDE 9m DROP
EFFECTIVE PLASTIC STRAIN ON OUTSIDE SURFACE

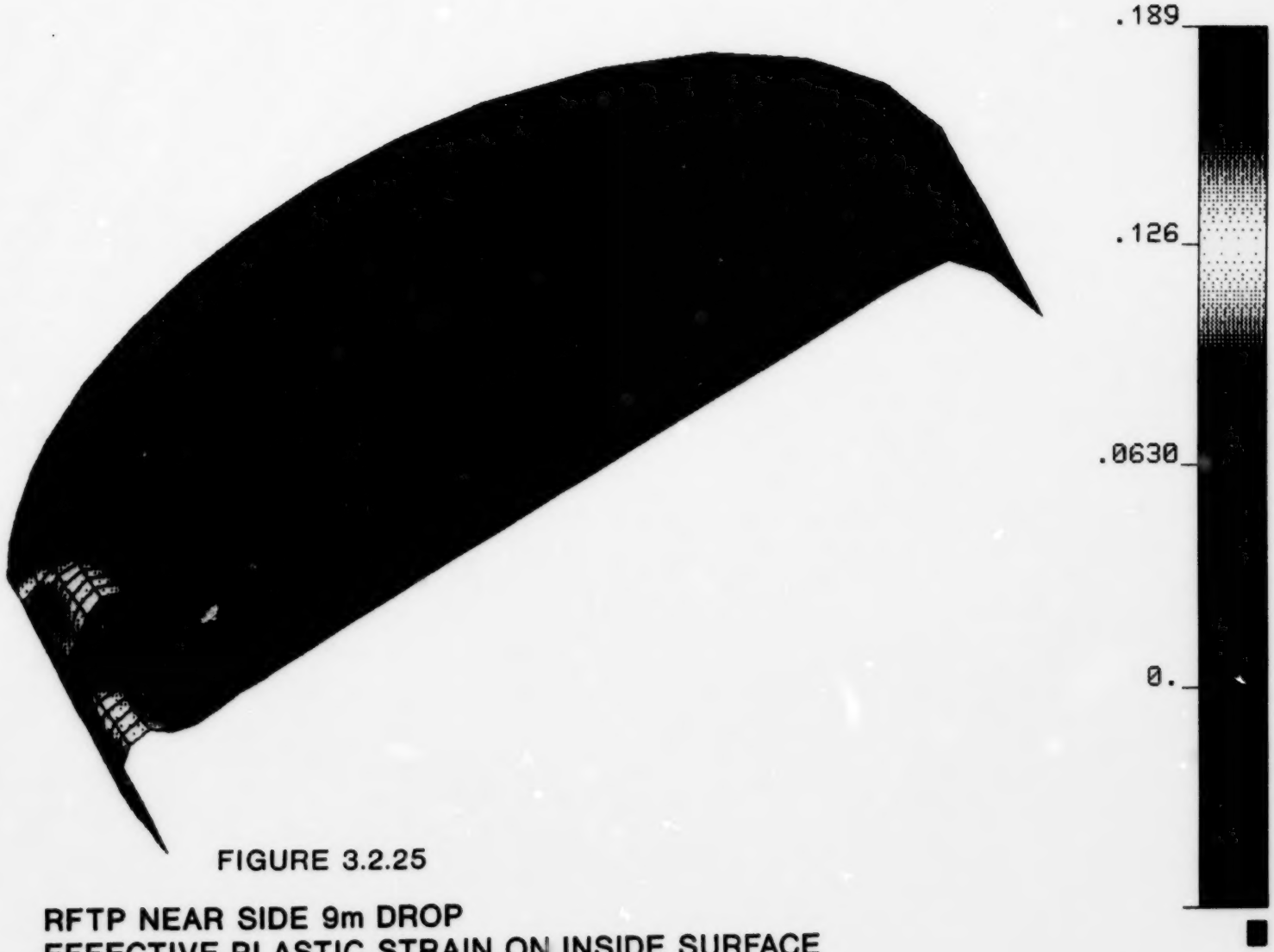


FIGURE 3.2.25

RFTP NEAR SIDE 9m DROP
EFFECTIVE PLASTIC STRAIN ON INSIDE SURFACE

FIGURE 3.2.26
RFTP NEAR SIDE 9m DROP
EFFECTIVE PLASTIC STRAIN ON OUTSIDE SURFACE

FIGURE 3.2.27
RFTP NEAR SIDE 9m DROP
EFFECTIVE PLASTIC STRAIN ON INSIDE SURFACE

FIGURE 3.2.28
RFTP NEAR SIDE 9m DROP
EFFECTIVE PLASTIC STRAIN ON OUTSIDE SURFACE

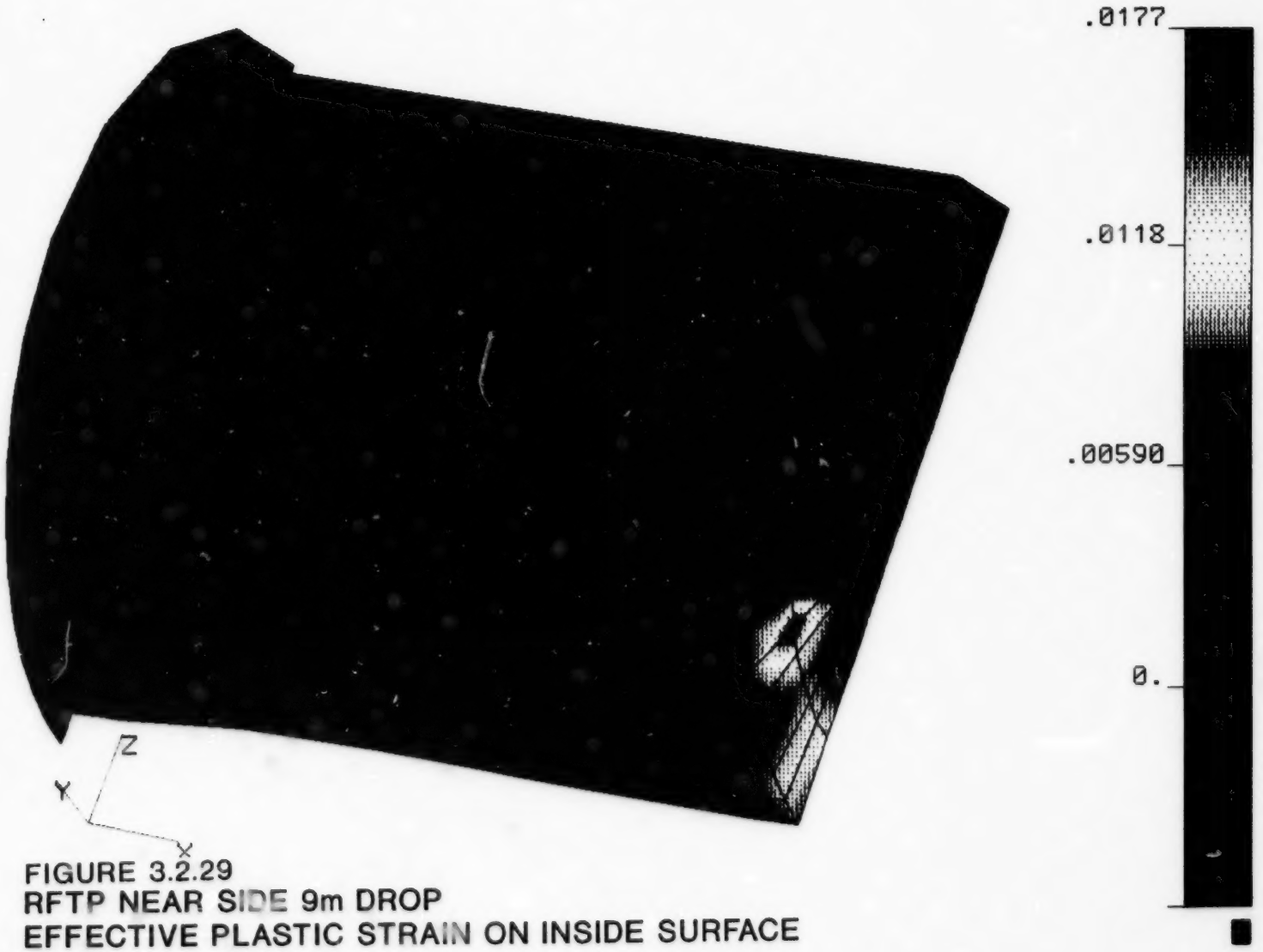


FIGURE 3.2.29
RFTP NEAR SIDE 9m DROP
EFFECTIVE PLASTIC STRAIN ON INSIDE SURFACE

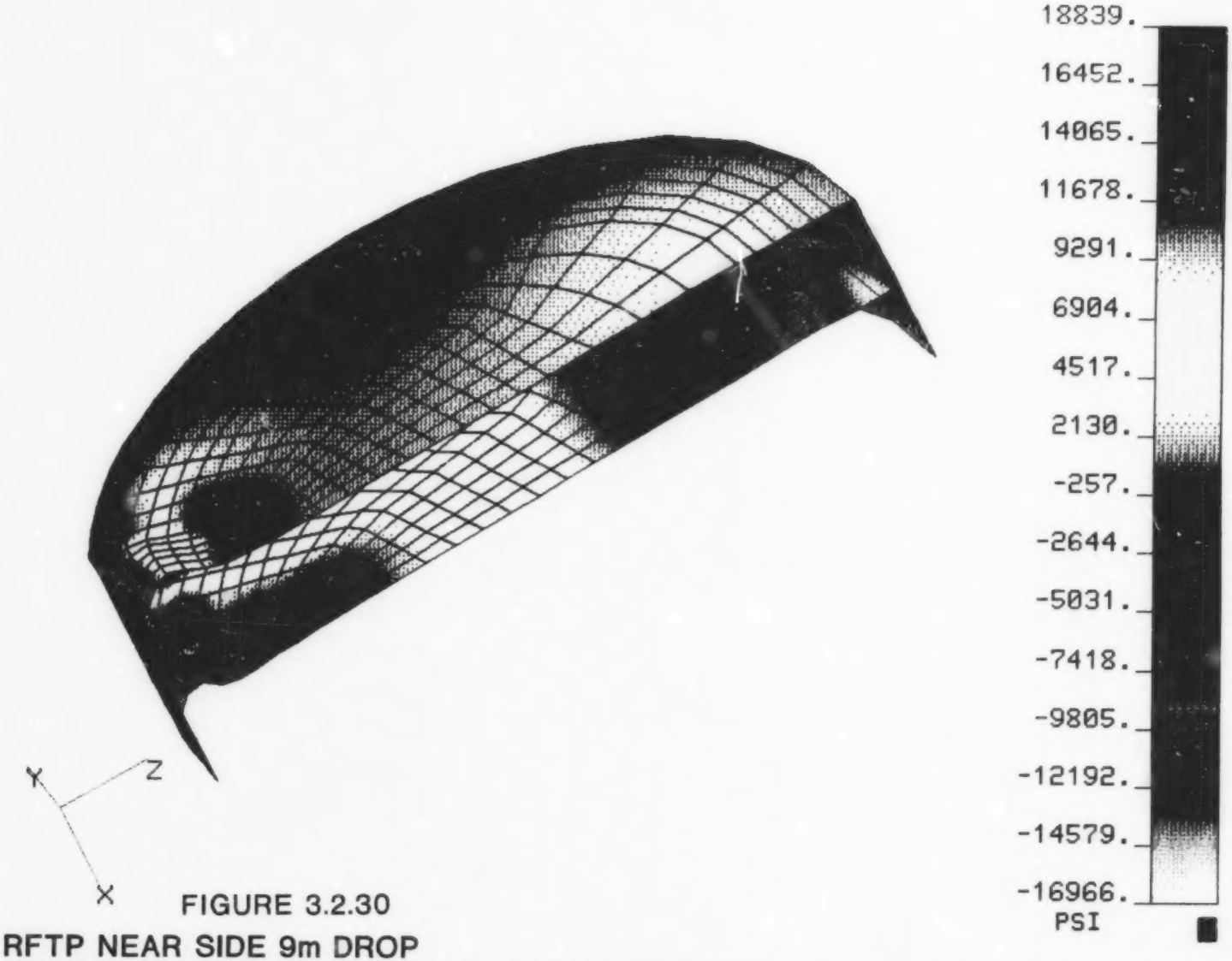


FIGURE 3.2.30

RFTP NEAR SIDE 9m DROP
HYDROSTATIC STRESS, MEMBRANE COMPONENT

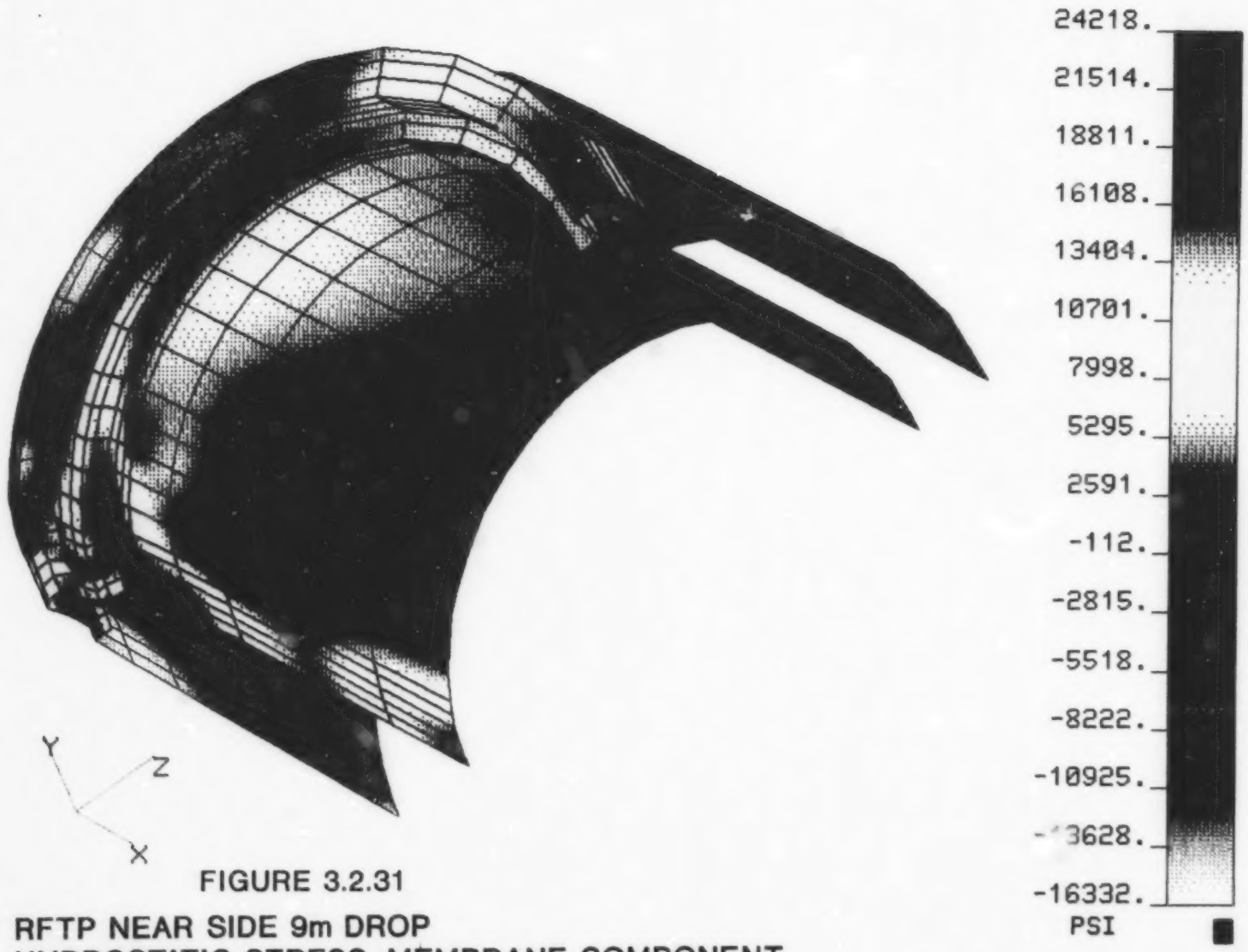


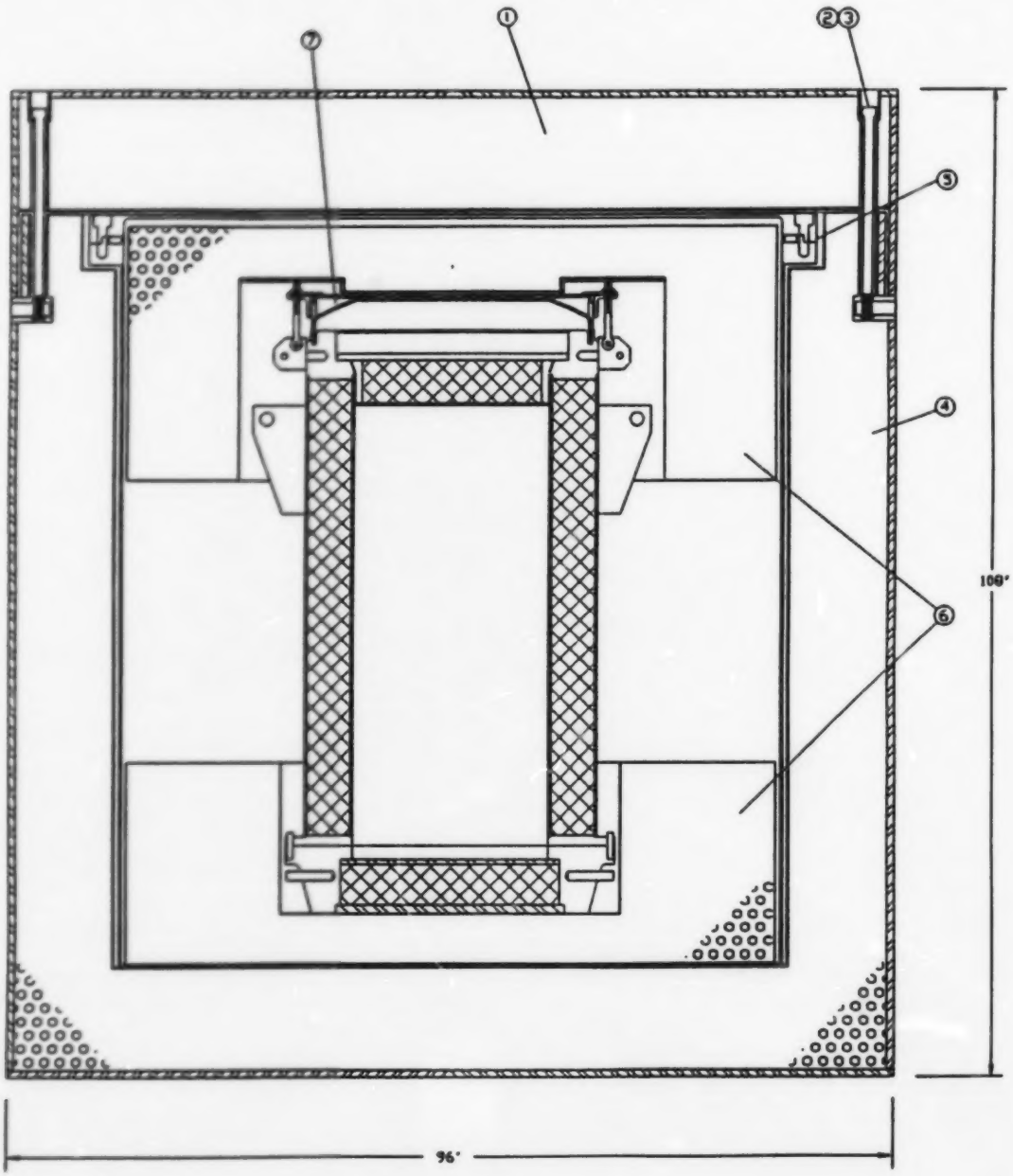
FIGURE 3.2.31

RFTP NEAR SIDE 9m DROP
HYDROSTATIC STRESS, MEMBRANE COMPONENT

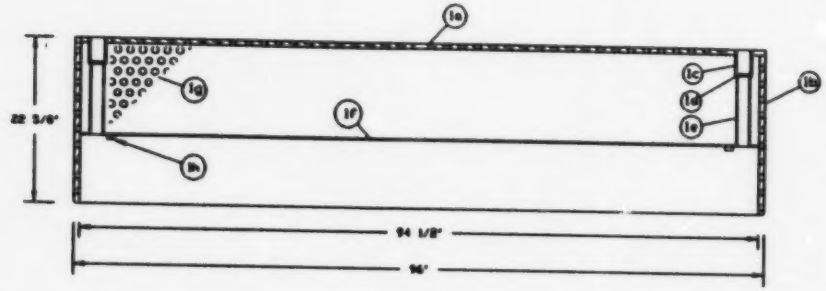
APPENDIX A1

RFTP STRUCTURAL DETAILS

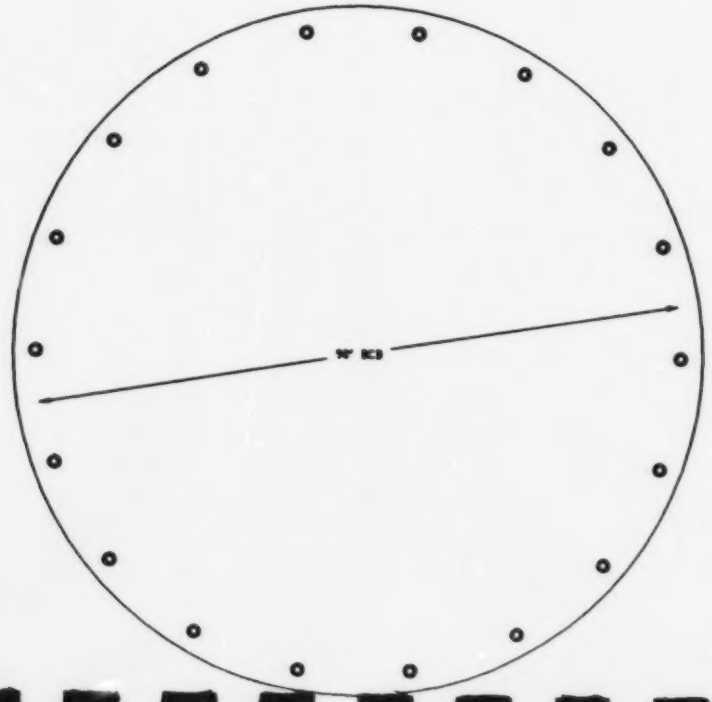
Radioactive Filter Transportation Package

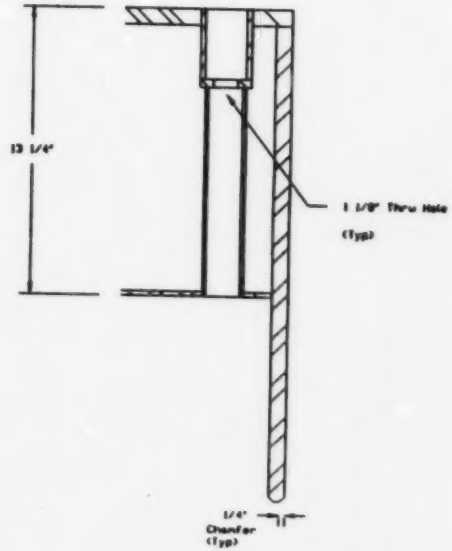


Item 1: Overpack Cover



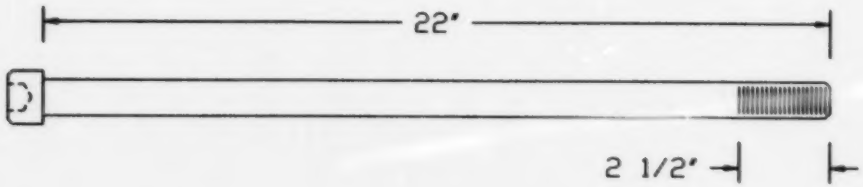
Item	Qty	Description	Material
1a	1	96" OD x 3/4" thk.	304 SS
1b	1	96" OD x 3/4" thk. x 21 7/8" High	"
1c	18	2" Sch 80 x 3 1/4" long Pipe	"
1d	18	2 3/8" Dia. x 1/4" thk.	"
1e	18	1.9" OD x .145" Wall Tubing x 9 3/4" long	"
1f	1	94 1/8" OD x 3/16" thk.	"
1g	As req'd	20 lbs/cu/ft Polyurethane Foam	
1h	1	82" ID x 85" ID x 1/2" thk Gasket	Sponge Material





90-1

Overpack Cover Bolts



Item 2

1"-8UNC-2A x 22" lng SHCS

Item 3

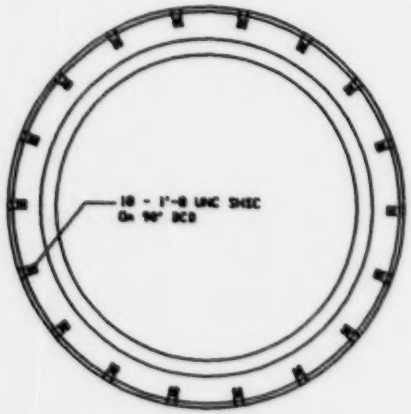
1" Nom. x 1/4" thk

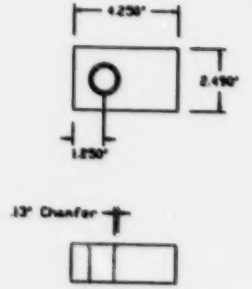
Helical Spring Lock Washer

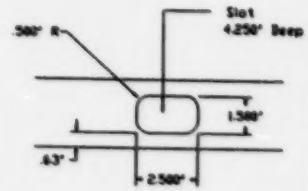
Item 4: Overpack Body

Item	Description	Qty	Material
4a	96" OD x 3/4" thk x 88 7/8" high	1	304 SS
4b	94" OD x 87" ID x 2 3/4" high	1	"
4c	4 1/4" long x 2 1/2" wide x 1 1/2" high	18	"
4d	93 3/4" OD x 3/4" thk x 9" high	1	"
4e	93 3/4" OD x 80 1/2" ID 1/8" thk	1	"
4f	1 1/2" Sch 40 pipe x 9 1/8" long	18	"
4g	80 3/4" OD x 1/8" thk x 5 7/8" high	1	"
4h	80 3/4" OD x 73" ID x 1/8" thk	1	"
4i	73 3/8" OD x 3/16" thk x 76 3/8" high	1	"
4j	73" OD x 3/16" thk	1	"
4k	96" OD x 3/4" thk	1	"
4l	20 lbs/cu.ft. polyurethane foam - as req'd		

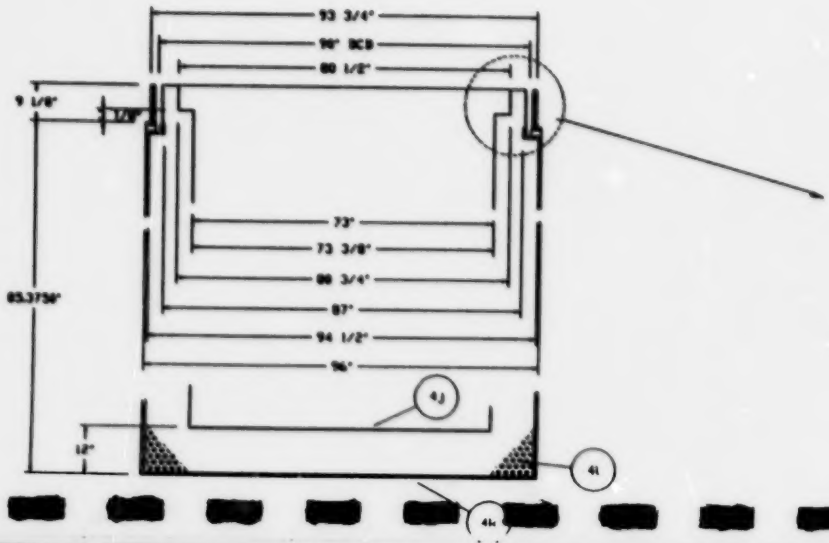
Item 4c - Inserts
Material 304 SS

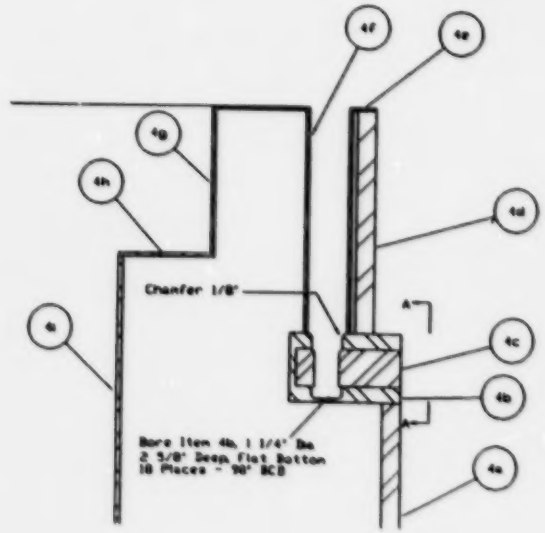






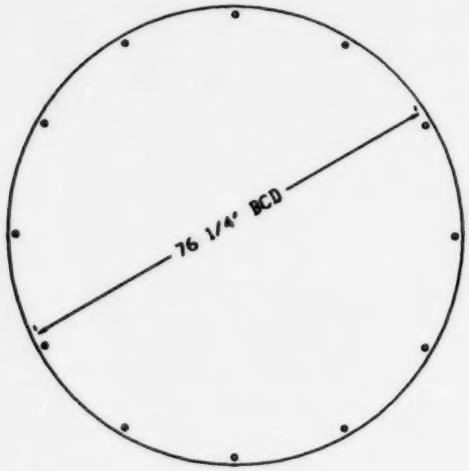
Section A-A

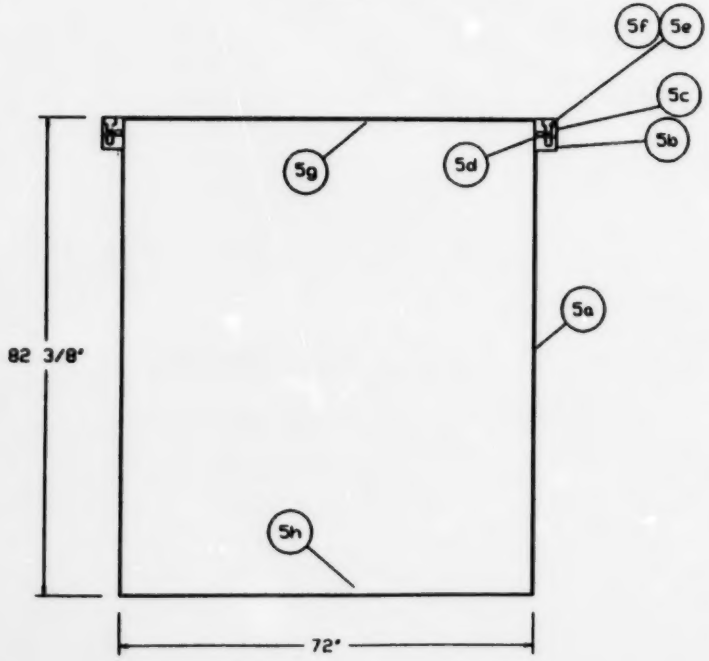


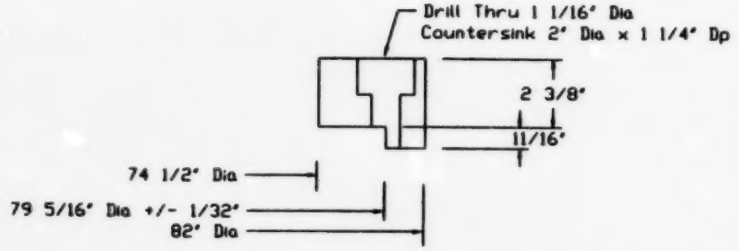


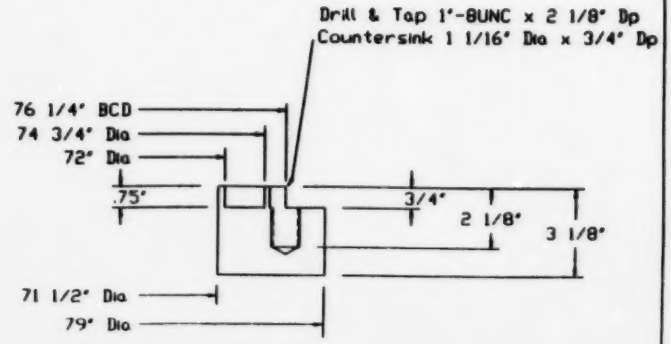
Item 5 Containment Vessel

Item	Qty	Description	Material
5a	1	72" OD x 1/4" thk x 76 5/8" high	304 SS
5b	1	79" OD x 71 1/2" ID x 3 1/4" high	304 SS
5c	1	79" OD x 71 1/2" ID x 3 1/4" high	304 SS
5d	1	74 3/8" OD x 72 3/8" ID x 1" thk	Silicon Gasket
5e	12	1"-8UNC x 3" lng x 2" Grip SHCS	304 SS
5f	12	1" x 1/4" thk Helical Lock Washer	SS
5g	1	71 1/2" OD x 3/8" thk.	304 SS
5h	1	72" OD x 1/4" thk.	304 SS

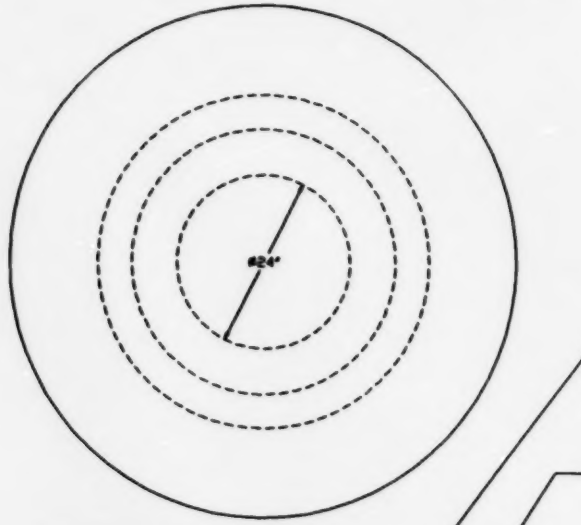


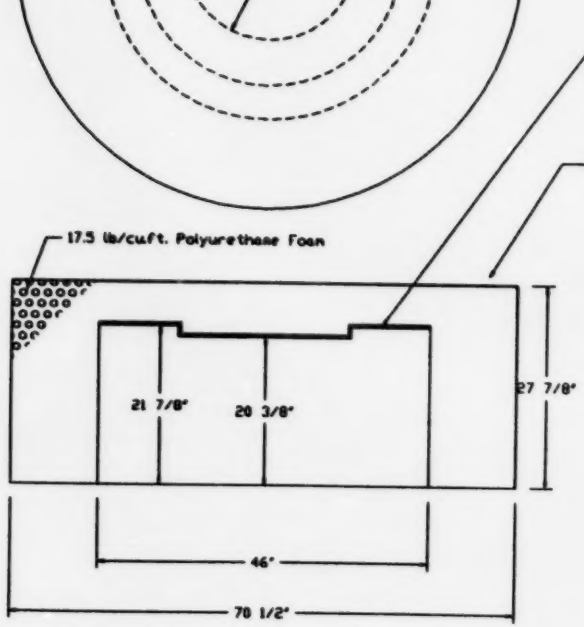


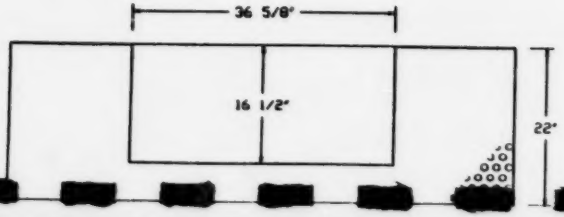




(6) Pickering 'B' Dunnage





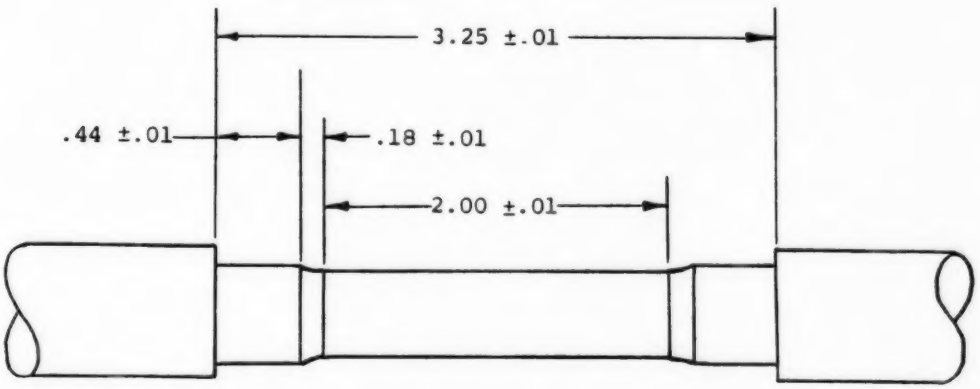


APPENDIX A2

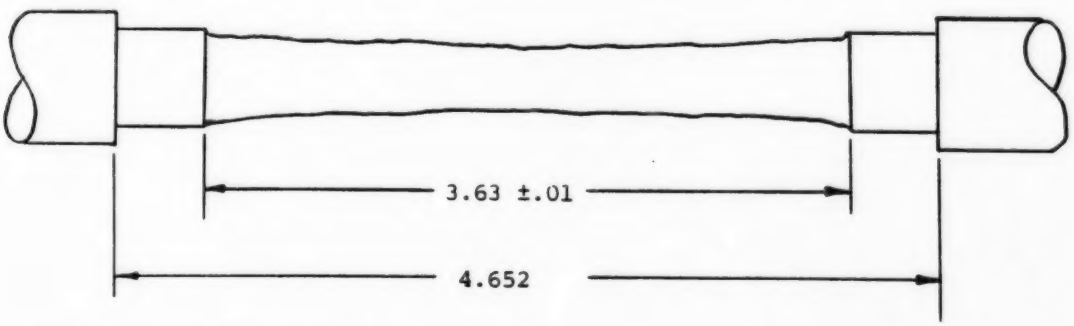
MATERIAL PROPERTIES FOR NITRONIC BOLTS

Uniaxial Tension Test for Nitronic Steel

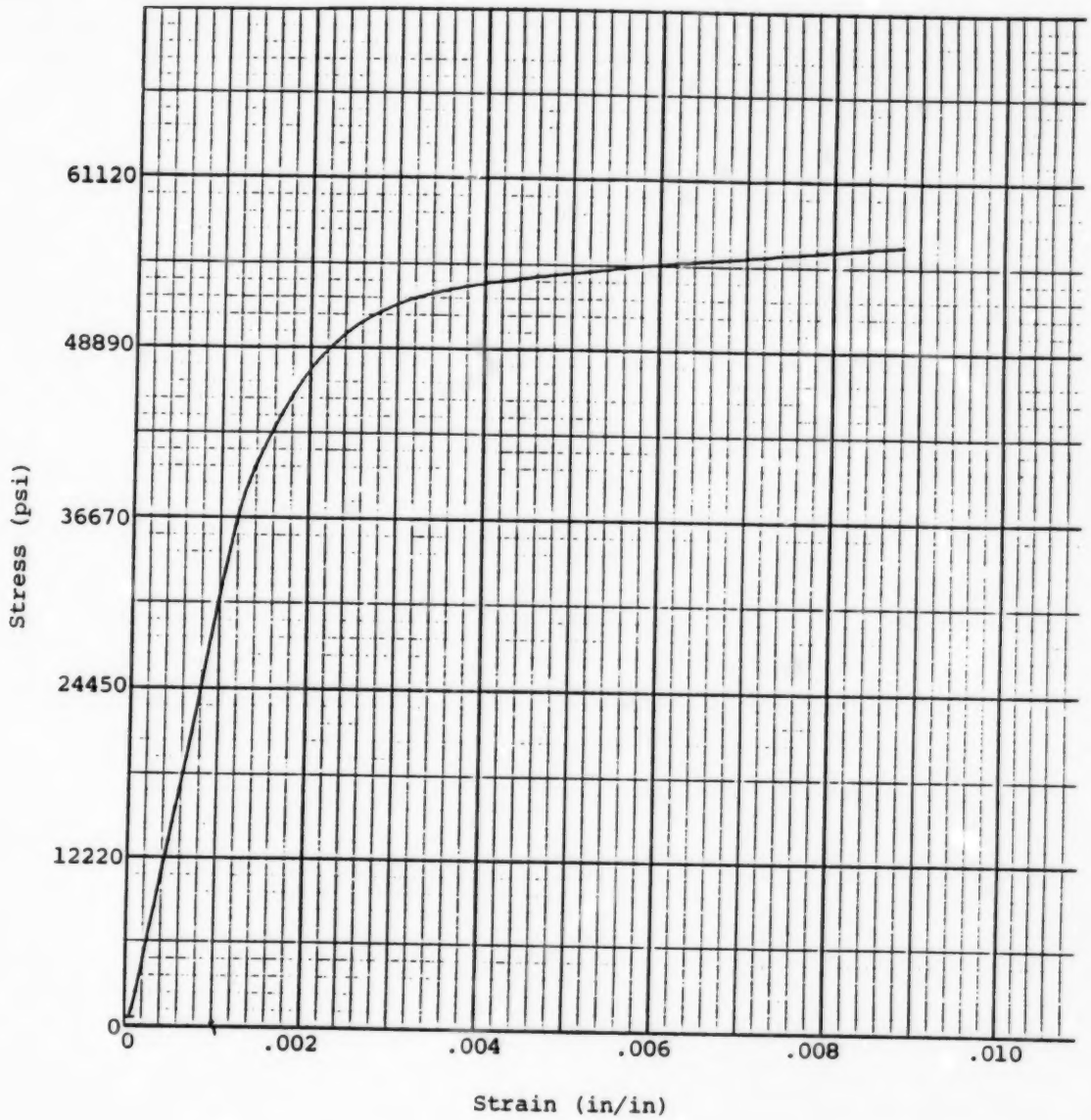
The test specimen was used to obtain the stress vs. strain curve for the Nitronic material. Following this, the extensometer was removed and loading was continued to examine post yield behaviour. The test was stopped when necking became visible. The maximum load during the test was 21100 lb. which corresponds to an engineering stress of 107,000 psi. The extent of deformation up to the point of necking is shown below where initial and final dimensions for the sample are given. The stress/strain curve and a detailed drawing are on the following pages.



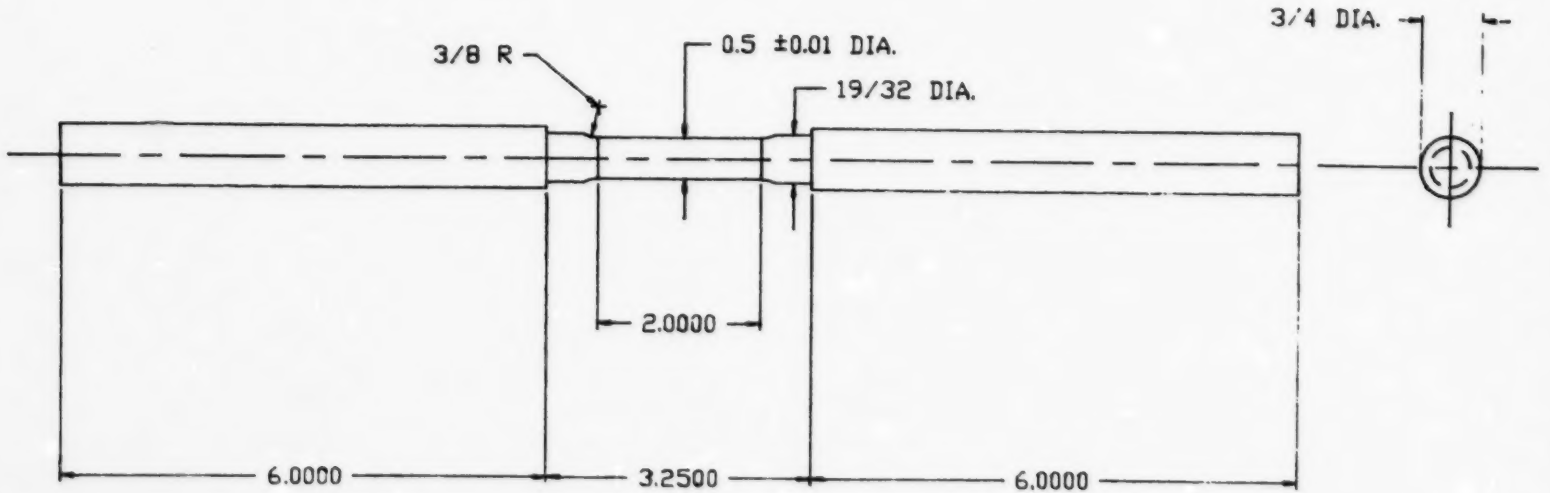
Initial Sample Dimensions



Final Sample Dimensions



STRESS VS. STRAIN CURVE FOR
NITRONIC STEEL BOLT MATERIAL



NOTE:
All dimensions are in inches

MATERIAL:
Nitronic 60 stainless steel

Ontario Hydro
research division
applied mechanics

RFTP NUMERICAL ANALYSIS
NITRONIC 60 SS
MATERIAL PROPORTY TEST

designed by: Cy Naumenko	approved by:
date	draftsman Cy Naumenko
scale 1:2	dwg no 001 / rev 01

APPENDIX A3

DERIVATION OF FOAM MATERIAL CONSTANTS a_0, a_1, AND a_2 FOR PRESSURE DEPENDENT FLOW RULE

DERIVATION OF FOAM MATERIAL CONSTANTS a_o, a_1, AND a_2 FOR PRESSURE DEPENDENT FLOW RULE

Basic relations for foam material models based on elementary isotropic plasticity theory:

Total Stress = Hydrostatic Stress + Stress Deviator

$$\sigma_p = \text{Hydrostatic Pressure} = \frac{-(\sigma_1 + \sigma_2 + \sigma_3)}{3}$$

where σ_i = principal stresses

Decomposition of stress tensor:

$$\sigma_{ij} = \sigma'_{ij} + 1/3\ \delta_{ij}\ \sigma_{kk}$$

where δ_{ij} = Krönecker delta

$$\therefore\ \sigma'_{ij} = \sigma_{ij} + \delta_{ij}\ \sigma_p$$

J_1, J_2, J_3 are the invariants of the <u>deviatoric</u> stress tensor

$$J_1 = (\sigma_1 + \sigma_p + \sigma_2 + \sigma_p + \sigma_3 + \sigma_p) = 0$$

$$J_2 = \frac{1}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_2)^2 + 6(\tau_{12}^2 + \tau_{23}^2 + \tau_{13}^2)\right]$$

for pure tension/compression

$$J_2 = \frac{1}{6}\left[2\sigma_1^2\right] = \frac{\sigma_1^2}{3}$$

for pure shear

$$J_2 = \tau_{12}^2$$

For foams the yield function is given as (analogous to yield function for metals):

$$\phi = J_2 - (a_o + a_1\sigma_p + a_2\sigma_p^2)$$

where σ_p is the hydrostatic pressure

$$\sigma_p = \frac{-(\sigma_1 + \sigma_2 + \sigma_3)}{3} \qquad \begin{matrix}(+\text{ ve compression}) \\ (-\text{ ve tension})\end{matrix}$$

The material is elastic when $\phi \leq 0$.

For uniaxial stress:

$$J_2 = \frac{\sigma_1^2}{3} \quad \text{and} \quad \sigma_p = -\frac{\sigma_1}{3}$$

and the yield surface is described by

$$\frac{1}{3}\sigma_y^2 - \left(a_o - a_1\frac{\sigma_y}{3} + a_2\frac{\sigma_y^2}{9} \right)$$

where σ_y is the yield stress.

The yield surface for any stress state can be described by:

$$a_o + a_1\sigma_p + a_2\sigma_p^2 = \frac{1}{3}\sigma_y^2$$

where σ_p is the hydrostatic pressure and σ_y is the equivalent uniaxial stress.

Calculation of a_o, a_1, and a_2 for 19 lb/ft^3 Polyurethane Foam

The values of the constants used in the flow rule were evaluated using the test data obtained for the 19 lb/ft^3 polyurethane foam, described in /13/. A parabolic curve (i.e., $a_2 = 0$) was utilized, since, as pointed out in /12/, this fits the data for such materials very well. From the test results, the tensile threshold or cut-off (i.e. $\sigma_y = 0$) was found to be:

$$\sigma_{po} = -223.84 \text{ psi (negative denotes tension)}$$

In addition, a pure shear test was conducted and the yield in shear was found to be:

$$\tau_{y1} = 149.39 \text{ psi.}$$

The corresponding yield in tension is:

$$\sigma_{y1} = \sqrt{3}\, \tau_{y1} = 258.74 \text{ psi}$$

Since this is a case of pure shear:

$$\sigma_{p1} = 0.$$

Substituting these values into:

$$a_o + a_1 \sigma_p = \frac{\sigma_y^2}{3} \qquad \text{(parabolic curve, } a_2 = 0\text{)}$$

leads to the equality:

$$\begin{bmatrix} 1. & -223.84 \\ 1. & 0 \end{bmatrix} \begin{Bmatrix} a_0 \\ a_1 \end{Bmatrix} = \begin{Bmatrix} 0 \\ \frac{258.75^2}{3} \end{Bmatrix}$$

Solving for a_o, a_1:

$$\underline{a_o = 22317.4}$$

$$\underline{a_1 = 99.7}$$

The final equation for the yield stress in terms of hydrostatic pressure is:

$$\underline{\sigma_y^2 = 3\,(22317.4 + 99.7\,\sigma_p)}$$

As implemented, the variation of σ_y with hydrostatic pressure σ_p is used for values of σ_p in compression only. When σ_p becomes tensile the value of yield, σ_y, stays constant at the value of σ_y corresponding to $\sigma_p = 0$. Once the tensile threshold is reached, the pressure is left at the cut-off value and the deviatoric stress components are zeroed.

The hydrostatic stress is governed by an equation of state relating pressure to volumetric strain whereas the pressure dependent flow rule governs the deviatoric behaviour.

As demonstrated in the experimental benchmarks performed in references 6, 7 and 8, the material model described above provides an acceptable representation of foam material. In fact, for the application considered, the foam material response is essentially governed by the equation of state.

APPENDIX A4

ACCEPTANCE CRITERIA

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In order to evaluate the RFTP design, some form of acceptance criteria is necessary to provide measures with which to compare the analytical results. The NUPACK committee formed by the American Society of Mechanical Engineers (ASME) to establish guidelines for the design of irradiated fuel transportation casks, have proposed stress and strain limiting criteria to be applied to the results of a structural analysis of impact. These criteria are intended to augment the basic stress and strain limits under level D loading conditions as given in Appendix F, Section III of the ASME code.

Appendix F does not address the problem of ductile tearing in the regions of high strains such as those existing at points of impact. This consideration is not required on account of the low values of general strain permitted under Appendix F. In addition, the hydrostatic stresses at the point of impact are usually compressive resulting in increased ductility and in a reduced tendency to crack initiation. Consequently, ductile tearing does not have to be considered in the impact region for cases involving a corner drop, edge drop or flat end drop. Thus, if hydrostatic stresses are compressive, strain limits are not imposed.

A different situation, however, may arise at the point of impact on a pin, as in a punch drop, where the hydrostatic stresses may be either tensile or compressive, and high shear stresses may cause ductile tearing.

In reference /15/, two strain limitations are suggested to protect against ductile tearing (when hydrostatic stresses are tensile):

(a) For membrane strains $\epsilon_m \leq 0.7\ Zn$

(b) For peak strains ϵ_{pk}:

$$\epsilon_{pk} \leq 0.7 \max \left(\left[\left[\frac{\sinh \left[\frac{\sqrt{3}}{3} (1-n) \right]}{\sinh \left[\frac{\sqrt{3}}{3} (1-n)(TF) \right]} \right], (0.2) \right] \bar{\epsilon}_f \right)$$

where $\bar{\epsilon}_f$ = true strain at fracture in uniaxial tension

TF = triaxiality factor = $\left(\frac{\sigma_1 + \sigma_2 + \sigma_3}{\bar{\sigma}_f} \right)$

$\bar{\sigma}_f$ = effective von Mises stress

n = strain hardening exponent in equation $\bar{\sigma} = A\ (B + \bar{\epsilon})^n$, which approximates the true stress-strain curve (Reference /11/) (i.e. n = 0.5 for stainless steel, n = 0.2 for carbon steel)

$$Z = \frac{\epsilon_{max}}{n}$$

Values of maximum strain at failure (ϵ_{max}) are readily available for some simple cases:

(a) Uniaxial tension $\epsilon_{max} = n$

(b) Pressurized cylinder $\epsilon_{max} = 0.577\ n$

(c) Pressurized sphere $\epsilon_{max} = 0.677\ n$

For other geometries and loading conditions the effective strain must be derived from the plastic instability condition ($dP/d\epsilon = 0$). This may present substantial difficulty when dealing with complex strain distributions and it may necessitate some conservative evaluation of the allowable effective strain.

Constants A and B in equation $\bar{\sigma} = A\ (B + \bar{\epsilon})^n$ can be obtained from the true stress-strain diagram. Chapter 10 of Reference /10/ gives this equation for some commonly used materials.

Using the above approach, allowables for peak and membrane strains for the RFTP stainless steel shells, when the hydrostatic stresses are tensile, are obtained assuming a predominant biaxial stress distribution as follows:

allowable membrane strain = $0.7 \times .577 \times .5 = 0.20$ (20%)

allowable peak strain = $0.7 \times \epsilon/\epsilon_f \times 0.5$

From Reference /15/ a value for ϵ/ϵ_f in a biaxial stress state is $\epsilon/\epsilon_f = 0.665$. Thus, the allowable peak strain = $0.7 \times \epsilon/\epsilon_f \times 0.5 = 0.23$ (23%).

Note that these allowables only apply to stress states where the hydrostatic component is in tension and true stress-strain properties are used.

Since the outer package is not a primary containment boundary, the full absorbing capability of the structure is taken, so that the allowable membrane strain = $0.20/0.7 = \underline{0.28}$ (28 percent), and the allowble peak strain = $0.23/.7 = \underline{0.33}$ (33 percent).

In order to apply these limits some interpretation of the analytical results is necessary. In the work described herein, the effective plastic strains and effective (von Mises) stresses in the stainless steel are obtained across selected sections of the finite element model. The resulting average and peak strains are obtained for elements whose hydrostatic stress component is tensile, and then compared to the allowable strain limits.

APPENDIX A5

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[DON.PACK1.NEWRUN]MASTER5.SHELLS;2        26  14-SEP-1989 13:20
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[DON.PACK1.NEWRUN]RFTP.SHELLS;2          140  23-OCT-1989 11:01
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[DON.PACK1.NEWRUN]S5.SHELLS;1             10  24-OCT-1989 08:58
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[DON.PACK1.POSTPAT.FOAM]LIDF.HYD;1       182  15-NOV-1989 12:07
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[DON.PACK1.POSTPAT.HYDPAT]INNERH.NEU;2   1179  13-NOV-1989 10:04
[DON.PACK1.POSTPAT.HYDPAT]INNERH.OUT;1     36  13-NOV-1989 10:06
[DON.PACK1.POSTPAT.HYDPAT]LIDH.IN;1        90   9-NOV-1989 15:25
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[DON.PACK1.POSTPAT.HYDPAT]OPACKHS.NEU;1  1279   9-NOV-1989 16:06
[DON.PACK1.POSTPAT.HYDPAT]OPACKHS.OUT;1    76   9-NOV-1989 16:08
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[DON.PACK1.POSTPAT]INNER.ELEM;1           119  26-OCT-1989 13:59
[DON.PACK1.POSTPAT]INNER.IN;1              36   2-NOV-1989 11:19
[DON.PACK1.POSTPAT]INNER.MEM;1             36   2-NOV-1989 11:19
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[DON.PACK1.POSTPAT]INNER.OUT;1             36   2-NOV-1989 11:19
[DON.PACK1.POSTPAT]LID.DUMP;1             697  26-OCT-1989 13:45
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[DON.PACK1.POSTPAT]LID.MEM;1               90  27-OCT-1989 09:41
[DON.PACK1.POSTPAT]LID.NEU;1             1315  27-OCT-1989 09:36
[DON.PACK1.POSTPAT]LID.OUT;1               90  27-OCT-1989 09:41
[DON.PACK1.POSTPAT]MASTER.NEU;1          1324   6-NOV-1989 12:09
[DON.PACK1.POSTPAT]MASTER_ALL.SHELLS;1     65   6-NOV-1989 14:14
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[DON.PACK1.POSTPAT]OPACK.ELEM;1           283  26-OCT-1989 10:35
[DON.PACK1.POSTPAT]OPACK.IN;1              76  26-OCT-1989 15:19
[DON.PACK1.POSTPAT]OPACK.MEM;1             76  26-OCT-1989 15:19
[DON.PACK1.POSTPAT]OPACK.NEU;1           1279  26-OCT-1989 15:16
[DON.PACK1.POSTPAT]OPACK.OUT;1             76  26-OCT-1989 15:19
[DON.PACK1.POSTPAT]RFTP.CORD;1            574  26-OCT-1989 08:37
[DON.PACK1.POSTPAT]RFTP.DEF;1             574  26-OCT-1989 10:24
[DON.PACK1.POSTPAT]RFTP.DUMP;1           1555  26-OCT-1989 08:40
[DON.PACK1.POSTPAT]RFTP.ELEM;1            740  26-OCT-1989 08:37
[DON.PACK1.POSTPAT]RFTP.NEU;1            2822   3-NOV-1989 14:23
[DON.PACK1.POSTPAT]SLAVE.NEU;1           1403   6-NOV-1989 12:04
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[DON.PACK1]SCRATCH.DIR;1                   14  11-AUG-1989 09:53
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[DON.PACK1.SCRATCH]BOTTOM_TEMP.CORD;1       9   6-SEP-1989 12:49
[DON.PACK1.SCRATCH]BOTTOM_TEMP.SHELLS;1     5   5-SEP-1989 13:36
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[DON.PACK1.SCRATCH]INNER_TEMP.SHELLS;1                8  20-OCT-1989 14:19
[DON.PACK1.SCRATCH]LID.BRICKS;1                     170  21-AUG-1989 15:08
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[DON.PACK1.SCRATCH]LID.SHELLS;1                     106  22-AUG-1989 09:25
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[DON.PACK1.SCRATCH]M3.SHELLS;1                       18  26-SEP-1989 10:36
[DON.PACK1.SCRATCH]M4.SHELLS;1                        2  26-SEP-1989 10:37
[DON.PACK1.SCRATCH]M5.SHELLS;1                       20  26-SEP-1989 10:37
[DON.PACK1.SCRATCH]M6.SHELLS;1                        3  26-SEP-1989 10:37
[DON.PACK1.SCRATCH]MASTER1.SHELLS;1                   3  25-SEP-1989 09:20
[DON.PACK1.SCRATCH]MASTER2.NEW;1                     13  28-SEP-1989 13:30
[DON.PACK1.SCRATCH]MASTER2.NEW1;1                    13  28-SEP-1989 13:31
[DON.PACK1.SCRATCH]MASTER2.OLD;1                     17  14-SEP-1989 10:12
[DON.PACK1.SCRATCH]MASTER2.SHELLS;1                  10  15-SEP-1989 12:58
[DON.PACK1.SCRATCH]MASTER3.OLD;1                     18  14-SEP-1989 10:39
[DON.PACK1.SCRATCH]MASTER3.SHELLS;1                  24  15-SEP-1989 13:03
[DON.PACK1.SCRATCH]MASTER4.SHELLS;1                   3  14-SEP-1989 10:53
[DON.PACK1.SCRATCH]MASTER5.SHELLS;2                  26  14-SEP-1989 13:20
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[DON.PACK1.SCRATCH]OPACK.CORD;1                     223  13-SEP-1989 10:42
[DON.PACK1.SCRATCH]OPACK.SHELLS;1                    53   8-SEP-1989 15:09
[DON.PACK1.SCRATCH]OPACK1_TEMP.CORD;1                 5   7-SEP-1989 12:57
[DON.PACK1.SCRATCH]OPACK1_TEMP.SHELLS;1               3   7-SEP-1989 12:57
[DON.PACK1.SCRATCH]OVER_TEMP.CORD;1                  20   8-SEP-1989 10:51
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[DON.PACK1.SCRATCH]S2.SHELLS;1                        6  26-SEP-1989 10:37
[DON.PACK1.SCRATCH]S3.SHELLS;1                       10  26-SEP-1989 10:38
[DON.PACK1.SCRATCH]S4.SHELLS;1                        9  26-SEP-1989 10:38
[DON.PACK1.SCRATCH]S5.SHELLS;1                        6  26-SEP-1989 10:38
[DON.PACK1.SCRATCH]S6.SHELLS;1                        3  26-SEP-1989 10:38
[DON.PACK1.SCRATCH]SKELETON.;1                        6  18-SEP-1989 08:10
[DON.PACK1.SCRATCH]SLAV.SHELLS;1                      8  23-OCT-1989 14:21
[DON.PACK1.SCRATCH]SLAVE1.SHELLS;1                   30  13-SEP-1989 13:12
[DON.PACK1.SCRATCH]SLAVE2.OLD;1                      13  13-SEP-1989 13:42
[DON.PACK1.SCRATCH]SLAVE2.SHELLS;1                    8  18-SEP-1989 08:36
[DON.PACK1.SCRATCH]SLAVE3.OLD;1                       5  13-SEP-1989 15:48
[DON.PACK1.SCRATCH]SLAVE3.SHELLS;1                   12  18-SEP-1989 08:45
[DON.PACK1.SCRATCH]SLAVE4.SHELLS;1                   11  14-SEP-1989 08:44
[DON.PACK1.SCRATCH]SLAVE5.SHELLS;1                    8  14-SEP-1989 08:14
[DON.PACK1.SCRATCH]SLAVE6.SHELLS;1                    3  13-SEP-1989 15:49
[DON.PACK1.SCRATCH]SLAVE_ALL.OLD;1                   99  14-SEP-1989 09:00
[DON.PACK1.SCRATCH]SLAVE_ALL.SHELLS;1               102  18-SEP-1989 09:34
[DON.PACK1.SCRATCH]TARGET.BRICKS;1                    5  21-SEP-1989 10:18
[DON.PACK1.SCRATCH]TARGET.CORD;1                     11  21-SEP-1989 10:18
[DON.PACK1]SIDE_DROP.DIR;1                            5  11-AUG-1989 09:48
[DON.PACK1.SIDE_DROP]CORNER.DISP;2                   19   1-NOV-1989 12:00
[DON.PACK1.SIDE_DROP]CORNER.FORM;2                    1   1-NOV-1989 12:02
[DON.PACK1.SIDE_DROP]CORNER.PLOT;1                   10   1-NOV-1989 13:59
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[DON.PACK1.SIDE_DROP]EDGELID.DISP;2                  92   1-NOV-1989 11:51
[DON.PACK1.SIDE_DROP]EDGELID.FORM;2                   2   1-NOV-1989 11:52
[DON.PACK1.SIDE_DROP]EDGELID.PLOT;1                  20   1-NOV-1989 11:52
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[DON.PACK1.SIDE_DROP]INLID.FORM;4                     1   1-NOV-1989 12:33
[DON.PACK1.SIDE_DROP]INLID.PLOT;1                    13   1-NOV-1989 12:33
[DON.PACK1.SIDE_DROP]INLID.VEL;1                     19   1-NOV-1989 12:30
[DON.PACK1.SIDE_DROP]INLIDV.FORM;1                    1  16-OCT-1989 10:47
[DON.PACK1.SIDE_DROP]INNER.ELEM;1                   119  26-OCT-1989 13:59
[DON.PACK1.SIDE_DROP]INNERNS.DUMP;1                 260  13-NOV-1989 10:23
[DON.PACK1.SIDE_DROP]INNERNS.IN;1                    36  13-NOV-1989 10:26
[DON.PACK1.SIDE_DROP]INNERNS.MEM;1                   36  13-NOV-1989 10:26
[DON.PACK1.SIDE_DROP]INNERNS.NEU;1                 1179  13-NOV-1989 10:24
[DON.PACK1.SIDE_DROP]INNERNS.OUT;1                   36  13-NOV-1989 10:26
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[DON.PACK1.SIDE_DROP]LID.DISP;2                          73   1-NOV-1989 11:45
[DON.PACK1.SIDE_DROP]LID.DUMP;1                         697   9-NOV-1989 15:59
[DON.PACK1.SIDE_DROP]LID.ELEM;1                         334  26-OCT-1989 10:30
[DON.PACK1.SIDE_DROP]LID.FORM;3                           1   1-NOV-1989 11:46
[DON.PACK1.SIDE_DROP]LID.HYD;2                          103   1-NOV-1989 13:48
[DON.PACK1.SIDE_DROP]LID.PLOT;1                          16   1-NOV-1989 11:46
[DON.PACK1.SIDE_DROP]LID3.DUMP;1                        279  21-NOV-1989 16:22
[DON.PACK1.SIDE_DROP]LID3.MEU;2                        1646  21-NOV-1989 16:27
[DON.PACK1.SIDE_DROP]LIDH.FORM;1                          2  16-OCT-1989 13:56
[DON.PACK1.SIDE_DROP]OLD_SIDE.RFTP_RUN;1                1457   5-OCT-1989 10:22
[DON.PACK1.SIDE_DROP]OPACK.DUMP;1                        589   9-NOV-1989 16:03
[DON.PACK1.SIDE_DROP]OPACK.ELEM;2                        264  15-NOV-1989 12:11
[DON.PACK1.SIDE_DROP]OPACK.FORM;3                          2   1-NOV-1989 13:52
[DON.PACK1.SIDE_DROP]OPACK.HYD;1                         104   1-NOV-1989 13:48
[DON.PACK1.SIDE_DROP]OPACK.PLOT;1                         20   1-NOV-1989 13:53
[DON.PACK1.SIDE_DROP]OPACK3.DUMP;1                       214  21-NOV-1989 16:25
[DON.PACK1.SIDE_DROP]PAYLOAD.DISP;2                       19  30-OCT-1989 15:47
[DON.PACK1.SIDE_DROP]PAYLOAD.FORM;3                        1   1-NOV-1989 13:56
[DON.PACK1.SIDE_DROP]PAYLOAD.PLOT;1                       11   1-NOV-1989 13:56
[DON.PACK1.SIDE_DROP]PAYLOAD.VEL;2                        19   1-NOV-1989 12:42
[DON.PACK1.SIDE_DROP]PAYLOAD.VEL;1                        19   1-NOV-1989 12:38
[DON.PACK1.SIDE_DROP]PAYLOADV.FORM;3                       1   1-NOV-1989 12:43
[DON.PACK1.SIDE_DROP]PAYLOADV.PLOT;1                      10   1-NOV-1989 12:43
[DON.PACK1.SIDE_DROP]RFTPS.;1                           1555  27-OCT-1989 10:24
[DON.PACK1.SIDE_DROP]RFTPS.CORD;2                        574  21-NOV-1989 16:12
[DON.PACK1.SIDE_DROP]RFTPS.DEF;1                         574  30-OCT-1989 10:04
[DON.PACK1.SIDE_DROP]RFTPS.DISP;1                       5161  30-OCT-1989 09:52
[DON.PACK1.SIDE_DROP]RFTPS.DUMP;1                       1555  30-OCT-1989 09:54
[DON.PACK1.SIDE_DROP]RFTPS.DYNA3D_INPUT;1               1555  27-OCT-1989 10:31
[DON.PACK1.SIDE_DROP]RFTPS.DYNA3D_LOG;1                   63  27-OCT-1989 10:31
[DON.PACK1.SIDE_DROP]RFTPS.DYNA3D_OUTPUT;1              2384  27-OCT-1989 10:31
[DON.PACK1.SIDE_DROP]RFTPS.DYNA3D_PLOTHIST;1            4012  27-OCT-1989 10:33
[DON.PACK1.SIDE_DROP]RFTPS.DYNA3D_PLOTSTRU;1            3844  27-OCT-1989 10:32
[DON.PACK1.SIDE_DROP]RFTPS.DYNA3D_RUN;1                    3  27-OCT-1989 10:31
[DON.PACK1.SIDE_DROP]RFTPS.ELEM;2                        740  21-NOV-1989 16:12
[DON.PACK1.SIDE_DROP]RFTPS.ELEM;1                        740  30-OCT-1989 09:51
[DON.PACK1.SIDE_DROP]RFTPS.FORCE;2                        21  31-OCT-1989 16:08
[DON.PACK1.SIDE_DROP]RFTPS.KE;1                           23  30-OCT-1989 09:17
[DON.PACK1.SIDE_DROP]RFTPS01.DYNA3D_PLOTHIST;1          3984  27-OCT-1989 16:48
[DON.PACK1.SIDE_DROP]RFTPS01.DYNA3D_PLOTSTRU;1          3424  28-OCT-1989 05:19
[DON.PACK1.SIDE_DROP]RFTPS01.DYNA3D_RESTART;1           2840  29-OCT-1989 04:00
[DON.PACK1.SIDE_DROP]RFTPS02.DYNA3D_PLOTHIST;1          3984  27-OCT-1989 23:54
[DON.PACK1.SIDE_DROP]RFTPS02.DYNA3D_PLOTSTRU;1           856  29-OCT-1989 03:26
[DON.PACK1.SIDE_DROP]RFTPS03.DYNA3D_PLOTHIST;1          3984  28-OCT-1989 06:57
[DON.PACK1.SIDE_DROP]RFTPS04.DYNA3D_PLOTHIST;1          3984  28-OCT-1989 15:19
[DON.PACK1.SIDE_DROP]RFTPS05.DYNA3D_PLOTHIST;1          1992  28-OCT-1989 23:47
[DON.PACK1.SIDE_DROP]RFTPS_3.DUMP;1                     1555  21-NOV-1989 16:13
[DON.PACK1.SIDE_DROP]RFTP_SIDE.NODES;1                   784  24-OCT-1989 11:42
[DON.PACK1.SIDE_DROP]TEMP.DUMP;1                        1555   9-NOV-1989 15:31

Total of 425 files, 167809 blocks
End of save set
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